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FUTURES:

Design exploration for the development
of fungi as a leather-like material.

Manuel Arias Barrantes

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MANUEL ARIAS BARRANTES

Master of Arts Thesis

MA in Creative Sustainability

School of Arts, Design and Architecture

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2019

To be human is to refuse to accept the given as given.

Susan Neiman

Aalto-yliopisto

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ABSTRACT

Living organisms such as fungi – *mycelium* – are opening a new paradigm for the manufacturing industry through the technology of biofabrication. To engage in this phenomena, designers and scientists are starting to collaborate in transdisciplinary contexts. However, little is known as to how this collaboration with experts takes place and even less how designers develop their interaction with living organisms in laboratories. Fungi possess a biological machinery of their own, which is often unknown to designers.

The research for this master's thesis took place primarily at the laboratories of VTT Technical Research Centre of Finland. This work explores how design processes using fungi can lead to sustainable alternatives to animal leather through the practice of biofabrication. I define this practice as a process that integrates living matter for the manufacturing of biological materials or products. The aim is to open the spectrum of physical materialities for fungi and through this practice understand the interaction between the designer and the living material as it grows and speaks to the designer. These materials are alive and possess an agency of their own. Through the interaction with fungi and the collaboration with scientists, this practice of design offers new possibilities to extend beyond the traditional forms of doing design. One is by engaging users in the process to explore material experiences and another one is by applying speculative design when exploring future applications for these materials.

The focus of this research lies on the practical design work in the laboratory. The methodology includes constructive design research, material design driven method and user involvements through two workshops and ten interviews. The contextual research includes the practices of speculative design and biodesign. Further research includes more centralized research on a single species of fungi, conducting a life cycle assessment, and internal research on the use of design practices in the context of laboratories.

Key words: Mycelium, fungi, sustainability, biofabrication, biodesign, speculative design, leather-like materials, animal leather.

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1: INTRODUCTION

1: INTRODUCTION

Materials have an important role in our society as they provide the means for manufacturing. However, conventional manufacturing processes are not always sustainable and can act as a threat to the well-being of people and the planet. One example is the animal leather industry, a material that could be distinguished as sustainable since it is a byproduct of the meat and dairy industry, but whose production is entitled to a diverse number of sustainability issues. These issues are associated to greenhouse gas emissions; land use; pollution of air, water, and soil; water use and availability; solid waste; animal welfare; health and safety of workers and community; and human rights.

On the contrary, living organisms such as fungi are opening a new paradigm for the manufacturing industry through the technology of biofabrication. This technology uses living matter to fabricate materials and products. Thus, promoting cleaner production methods. It does not require the extraction of raw materials from Earth's surface, can consume less energy than current manufacturing processes, the products and materials are biodegradable (although animal leather is biodegradable), does not use any chemicals, and their disposal does not harm the environment.

The practice of biofabrication has resulted in designers and scientists coming together in laboratories to explore the creation of new materials. However, there is currently very little knowledge as to how this collaboration with experts takes place and even less how designers develop their interaction with living organisms in laboratories. Inspired by this opportunity, I was encouraged by Pirjo Kääriäinen and invited by VTT Technical Research Centre of Finland to explore fungi – mycelium – to explore how leather-like materials could be developed and how this type of transdisciplinary collaboration could be better understood.

My initial endeavors with materials and their possible uses began a few years back with my own brand of accessories made out of recycled materials. Later, during my studies at Aalto University in the Creative Sustainability master's programme, I had the opportunity to explore the topic of fungal materials during CHEMARTS Summer School. Little I knew at that time, how much I would transcend from the traditional methods, processes, and tools of design practice to learn and apply those from biology as I dove into the realm of living organisms.

Situated at the intersection of design and biology, my aim is to provide a general view on the practice of biofabrication. My relationship, dependency, and responsibility with the living organism was built upon my interaction with it. The experiments were the medium upon which I was able to build a relationship with this living organism. The process of growing the materials resulted in a certain dependency as we engaged to learn from each other. Responsibility was required at every step of the process as I adopted traditional laboratory techniques and crafted my own design methods to feed, understand, and co-design with fungi. The material samples and the material experiences attached to them are the result of all laboratory work. Their unfinished, rough, and organic aspect invite us to explore further the kingdom of fungi. This was made possible thanks to the collaboration with several experts from the field of biology and the integration of our disciplinary practice and knowledge.

This work is enclosed under the umbrella of *biodesign* and applies some of the principles of *speculative design*. *Chapter 2: Background* is composed of three sections. In the first section, I describe the sustainability issues associated with the supply chain of animal leather. In the second section, I define the technology of biofabrication, state its context, cover its relevance for Europe and Finland, state the advantages and challenges, and conclude with some examples. In the last section of the chapter, I introduce the topic of leather-like materials and the research questions.

Chapter 3: Methodology and Structure is divided in four main sections. In the first section, I discuss the topic of collaboration between design and biology. In the second section, I define the research approach of Constructive Design Research. In the third section, the Material Driven Design (MDD) method is introduced. The last section concludes with the adaptation of the MDD method as well as the parts that conform the method in the context of this research.

In *Chapter 4*, I introduce speculative design and biodesign by analyzing the work of the most prominent scholars, researchers, and designers involved in the development of those two emerging practices. When discussing about speculative design, I review the relevance of designing for alternate futures and cover the most relevant arguments of speculative design. When analyzing the topic of biodesign, four different aspects are appraised. I first review the topic of biodesign by offering a general view. Then, I proceed to identify briefly the differences between what is natural and what is artificial. Next, I express my perspectives on the upcoming (bio) material designers. The chapter ends by discussing the definition of a pathway for biodesign.

Chapter 5: The Process of Biofabricating with Mycelium, Is the backbone of this research. This chapter is divided into six sections. The first two sections called *The Laboratory as a Space for Transdisciplinary Collaboration* and *The Laboratory as a Space for Material Exploration* cover the topic of collaboration and the material exploration based on my personal experience within the context of scientific laboratories. The section that follows, *Biofabricating with Mycelium*, introduces mycelium and the technical aspects related to its growing processes. The last three sections are devoted to my own design process. *Material Exploration: Understanding the Material in the Laboratory*, introduces all the experimentation that took place at the laboratory. *Material Analysis: Creating Material Experiences and Future Visions with Users* reveals the material experiences and future applications obtained through the workshops and interviews. The last section, *Material Prototypes: Unfolding Alternate Material Futures* presents the end result and the speculations formulated around the three main material samples.

This work closes with *Chapter 6: Conclusions*, where I discuss the validity of the research, its limitations and considerations for the future. The references are found after this last chapter as well as the *Appendix*.

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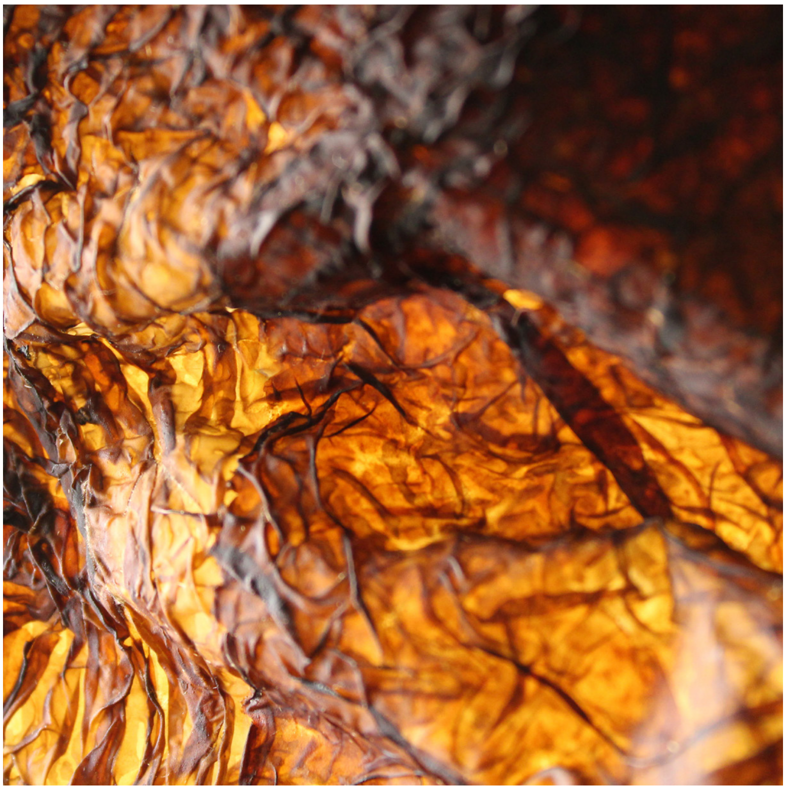
Figure 1. Scraping spores of *B. robillardoides*.

2: BACKGROUND



2: BACKGROUND

Materials have a long history of providing solutions to attend our human needs in the form of products, for the most part, but the increasingly obvious environmental and social impacts of their production have led entrepreneurs, designers, scientists and businesses to look for more sustainable alternatives. This is of particular relevance to one of the most polluting industries in the world, the clothing and textile industry. This industry alone has an ecological footprint far from sustainable. It emits 1.7 billion tons of CO_2 annually, is responsible for extensive water use and pollution, and produces 2.1 billion tons of waste annually (WWF, 2017, p. 3).

Animal leather, a biodegradable material with a high cost environmentally and socially, is the most common animal product used for clothing and accessories. This material is a major source of income for luxury brands and, in recent years, has become a material sought after by fast-fashion brands as well. This wide interest for this material means that soon we will need to shift from killing 290,000,000 cows every year, from a global herd approaching 1 billion, to slaughtering 430,000,000 annually by 2025 (Siegle, 2016). But, what if we could use design, biology, and technology to disrupt this industry and create an alternative material?

Taking the animal leather industry as the main point for comparison in this work, in the first section of this chapter, I cover the sustainability issues associated with it. These issues are identified by looking at the supply chain and analyzing the issues found at the different stages of production. However, even though it is estimated that synthetic leather (a.k.a. faux leather or fake leather) has only one third of the environmental impact of cow leather (Global Fashion Agenda & The Boston Consulting Group, 2017); different leathers - natural or synthetic - can have over tenfold difference in environmental impact based on their type and origin, how the animal was raised, and how the tanning process took place (Origem, 2017).

In the second section I cover the topic of biofabrication as a practice that is employed to counteract the sustainability issues of animal leather production. In the last section, I introduce the topic of fungal leather-like materials as a future alternative to animal leather. Due to the various properties of fungi as a soft material, this material is referred to in this thesis as *fungal leather-like* or *leather-like material (derived) from fungi* as it does not try to substitute animal leather, but rather to serve as a new alternative material to animal leather.

2.1 ANIMAL LEATHER: SUSTAINABILITY ISSUES IN THE SUPPLY CHAIN

The use of animal leather has existed since early times. The practice began with the need to use the animal as a source for food and from there using the remains for tools, shelter, clothing, etc. The practice expanded with the rise of agriculture and livestock (Kite & Thomson, 2006). Nowadays, most animal leather is produced as a byproduct of the meat and dairy industry (Ozgunay et al., 2007). It is estimated that 66% of leather comes from cows, 15% from sheep, 11% from pigs, 7% from goats, and 1-2% from other animals (UNIDO, 2010). In this sense, animal leather production could have been distinguished as a sustainable process since it uses the waste from the meat and dairy production. However, the traditional manufacturing processes used by this industry are associated with several sustainability issues.

The products made from animal leather extend from consumer goods to luxury items and belong to a complex and global supply chain. This supply chain is divided into three phases (Origem, 2017). The first phase covers the part of the supply chain from animal to raw hide or skin, the second phase goes raw hide or skin to leather, and the third phase covers the leather end products. Each of these phases include different steps with a number of sustainability issues attached to them *(Figure 2)*. These issues are associated to greenhouse gas emissions; land use; pollution of air, water, and soil; water use and availability; solid waste; animal welfare; health and safety of workers and community; and human rights (Ernst & Young, 2013). Each of these topics is discussed in the next section. The information was collected taking as reference all types of animal leather. Given the number of factors that come into play, the distinction of the animal per issue is beyond the scope of this research.

2.1.1 Greenhouse Gas Emissions

It is estimated by the Food and Agriculture Organization of the United Nations that livestock is responsible for 9% of all atmospheric CO_2 derived from human-related activities (FAO, 2006a). It generates 65% of human-related nitrous oxide, which has 296 times the Global Warming Potential (GWP) of CO_2. The causes for CO_2 emissions in livestock come from feed production, on-farm use of energy, land use change, methane released from enteric fermentation (digestive process in ruminant animals), manure, and transport (FAO, 2006a). Furthermore, in the preparation of the raw hides, organic waste (e.g. fleshings) is commonly dumped in open land, producing substantial amounts of methane (Kanagaraj, J. et al., 2015). Another source for emissions in this phase comes from the transportation of hides and skins, which many times cover large distances (UNIDO, 2017). The same is said about the phase of leather products as they need to be transported to their final destination. For the remaining phases, the greenhouse emissions are mostly related to energy use (Ernst & Young, 2013).

2.1.2 Land Use

Livestock is accountable for the largest use of land. In global terms, 20% of all pastures and 70% of all grazing land in dry areas are considered no longer arable (FAO, 2006b). The acquisition of land for livestock elicits the destruction of protected land and many times leads to indigenous people being victims of discrimination as they occupy these lands (FAO, 2006a). Deforestation of land for livestock purposes also results in biodiversity loss, erosion, climate change, and water scarcity (FAO, 2006a).

2.1.3 Pollution of Air, Water, and Soil

Livestock produces 64% of the world's anthropogenic ammonia emissions, mostly consisting of manure (FAO, 2006a). This causes eutrophication and acidification in water ways. Eutrophication happens when water becomes overly enriched with nutrients and causes accelerated growth of plant life (e.g. algae), diminution of oxygen in the water, and death of living organisms (e.g. fish). On the other hand, acidification occurs when the pH of soil and water is reduced by acids. This causes plant growth problems and the reduction of living organisms (Doney et al., 2009). Pollution is also emitted from slaughterhouses. It derives from organic matter being discharged in the waste water. Its decomposition requires oxygen, which causes a lack of sufficient oxygen content in the water needed to sustain other organisms naturally present downstream (Abdel-Raouf et al., 2012). During the preparation of the raw hides, pollution is generated from the use of chemicals which are many times discharged in the water without proper treatment (World Bank Group, 2007). In terms of tanning, the issues are also associated with the use of many different chemicals such as acids, alkalis, chromium salts, tannins, solvents, sulphides, dyes, auxiliaries, and many other compounds (Lofrano et al., 2013). The pollution issue is similar in the crusting and finishing stage as it derives from the use of chemicals and their disposal (COTANCE & IndustriAll-Europe, 2018).

2.1.4 Water Use and Availability

Water is a resource used extensively throughout the entire supply chain of leather production. Freshwater is used the most by the agricultural sector worldwide, partly by the fact that livestock require a big percentage for feed production as well as drinking and servicing water (not for drinking, but rather for industrial purposes) (FAO, 2006a). The treatment of the raw hides is the most water intensive of all the phases as it requires 20 – 25 m^3 per ton raw hides. This accounts for more than half the total water use (34-40 m^3) in the entire supply chain (European Commission, 2013). Additionally, slaughterhouses also require large amounts of water, about 6-15 liters per kg carcass (FAO, 2006a). This excessive use of water throughout the entire supply chain of leather production affects ecosystems and creates biodiversity loss, especially in areas where this resource is already limited (Ernst & Young, 2013).

2.1.5 Solid Waste

Waste is generated in various forms throughout the entire supply chain of leather production. In livestock, the manure produced causes problems associated with the already mentioned issues in greenhouse gas emissions and pollution of air, water, and soil. In the slaughtering process waste includes animal by-products, sludge from waste water treatment, protective clothing, and equipment (European Commission, 2005). When treating the raw hides, it is estimated that finished leather results in only 20-25% of the total weight of raw materials, the rest is considered waste or low value byproducts (Mavrodin et al., 2015). In tanning, the solid waste comes from chrome shavings and chrome splits since leather is disposed containing chrome (Fela et al. 2011). Lastly, in the manufacturing of products, most of the waste produced comes from cut-offs and damaged or defective leather pieces which are disposed. Waste is also generated upon the disposal of the products (Senthil et al., 2015).

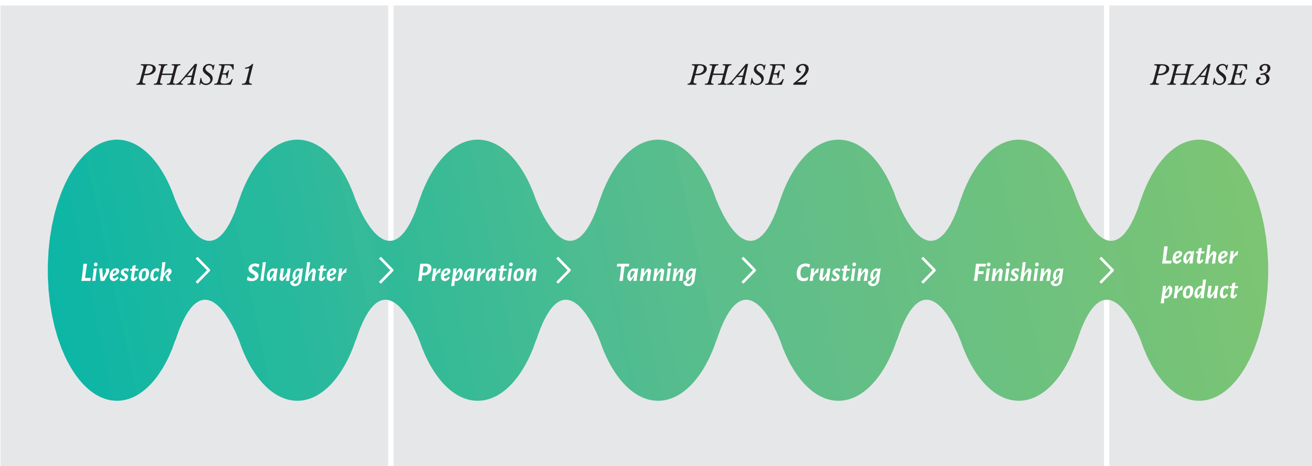


Figure 2. Phases and steps of the leather supply chain. Adapted from *Sustainability in the leather supply chain: Research for MVO Nederland* (p. 4), by Ernst & Young, 2013, Netherlands: Ernst & Young. Copyright 2013 by Ernst & Young. Adapted with permission.

2.1.6 Animal Welfare

The welfare of animals is one of the most talked about issues in leather production. These issues begin in livestock rearing since their welfare is threatened by inadequate housing and management during activities such as castration, branding, feeding, weaning, etc. (Origem, 2017). Issues continue in the slaughtering process as it involves the transport of the animal and further handling, housing, and inspection once they reach the slaughterhouse (Velarde & Dalmau, 2012). Once in the slaughterhouse, animals are stunned to make them insensitive to pain before the slaughter through the practice of exsanguination - blood loss until the animal is dead (FAO, 2001). During the stunning, slippery floors might cause the animal to fall on the floor or become unconscious if stunned incorrectly (Velarde & Dalmau, 2012).

2.1.7 Health and Safety of Workers and Community

There are many issues related to the topic of health and safety of workers and community. In livestock, inadequate working conditions cause numerous injuries and deaths from animals every year (Dohan & Demirci, 2012). These workers are also at risk of many diseases including, but not limited to, water-borne bacterial and viral pathogens such as salmonella spp, viral diseases, and livestock parasitic diseases (FAO, 2006a). Moreover, in slaughterhouses, workers are exposed to an environment that could lead to psychological damage (Dillard, 2008). The chemical-related activities required by workers in the stages of preparation of hides, leather tanning, and finishing puts their health and safety at risk, for example increased chances of skin diseases (Febriana et al., 2012). In fact, it is estimated that more than 80% of all leather produced is tanned using chromium salts, of which Chromium III is the

Figure 3. Leather tanneries of Fez in Morocco.

most dangerous at high concentrations (Basaran et al., 2008).

2.1.8. Human Rights

Violation of human rights are found throughout the three phases of leather production. It covers child labor, forced labor, and unfair wages. In livestock, most child labor happens through cattle herding. In some ethnic groups, cattle herding done by children is an accepted activity, but this becomes an issue worth addressing in circumstances where children are employed by companies; their schooling is interfered; or their mental, physical, phycological, or moral development faces harm (FAO, 2013). Children who are taken to work, many times do not have protective equipment, which exposes them to a number of injuries and illnesses (Dohan & Demirci, 2012). Child labor practices occur most frequently in the stages of tanning, crusting, finishing, and production of leather products (SOMO, 2012). On the other hand, forced labor can affect men, women, and children and is an issue present in all phases, which happens most often in remote areas (ILO ,2017). Lastly, unfair wages are paid throughout all three phases. In many countries the minimum wage is even below a living wage. For instance, during the preparation of hides, workers work long hours and are paid low wages while being exposed to dangerous chemicals and poor working conditions (SOMO, 2012).

2.2 BIOFABRICATION: A NEW PARADIGM FOR MANUFACTURING

The 21st century is experiencing a *bioeconomy* - an economic model consisting of utilizing renewable biological resources for the production of food, energy, products, and services, as well as creating new value from waste streams (Biotalous, 2014; Adamowiocz, 2014). It also includes those innovations and technologies employed for a given production (Bosman & Rotmans, 2016). The European Union and Finland have recognized its potential, and new opportunities such as biofabrication are opening a new paradigm for manufacturing.

For the European Union, the bioeconomy sets forward their promise to meet crucial sustainability challenges. This includes global warming, rapid urbanization growth, and the increasing use of natural resources. Moreover, the bioeconomy strategy contributes to fulfil global commitments including the Sustainable Development Goals and the Paris Agreement. By shifting to the bioeconomy model, it is estimated that Europe could save nearly 2.5 billion tons of CO_2 per year by 2030 (European Commission, 2018).

In the context of Finland, the model signifies a latent source for investment. The country currently holds a €60 billion turnover from the bioeconomy sector and is Europe's hub for bioeconomy. For example, research on leather-like materials from fungi contributes to providing future responsible uses of Finland's 86% of land currently covered by forests where different types of fungi inhabit (Biotalous, 2014).

Biofabrication is one of the many routes to a bioeconomy. This technology corresponds to the greater landscape of biotechnology. It is driven by biology, engineering, and technology coming together and opening new opportunities for practicing design among those disciplines. In contrast to basic science, which is interested in observation, modeling, and explanation of natural phenomena; what makes biofabrication unique is the use of technology to *engineer* nature using its own biological algorithm (Mironov et al., 2009). In this sense, the prefix *bio-* suggests that either the raw materials (e.g. biological molecules, extracellular matrices, living cells and tissues), processes, final materials or product constructs, or a combination of these, have been inspired by or based on the principles of biology. On the other hand, *fabrication* denotes the creation of something from a raw material or making something new based on its original constituents (Mironov et al., 2009).

From the above, biofabrication can be defined as a process that incorporates biology, engineering, and technology to manufacture complex biological materials or products using living organisms (Mironov et al., 2009; Pavlovich et al., 2016; Fujii et al., 2016). In this work, *life* (e.g. living organism) is understood as a process where one or more cellular entities exist in a given environment by virtue of growth, reproduction, metabolism, responsiveness, and adaptation (Alberts, 1994). As a clarification, biological molecules in isolation are non-living and are products of the cellular machinery, and as such do not fit within the definition of biofabrication. Instead, they belong to the fields of synthetic biology or biomaterials science (Mironov et al., 2009). However, there are instances when overlapping between practices occur if their definitions are explored more broadly. To some extent, biofabrication, synthetic biology, and biomaterials science can be allocated within the field of biotechnology.

Biofabrication originated from biomedicine, but the emergence of a new research community around this field has expanded its applications from the biomedical industry (e.g. organ printing) to new areas such as energy production (e.g. biofuel production from algae), food production (e.g. meat grown in laboratories) as well as the development of sustainable materials for manufacturing (Mironov et al., 2009). The latter encapsulates the motivation and importance for developing fungal leather-like materials.

The application of biofabrication in the manufacturing of sustainable materials targets crucial sustainability issues such as those faced by the leather industry. Therefore, biofabrication has great advantages compared to traditional technologies. For example, it does not involve the extraction of non-renewable raw materials since living organisms can be grown using renewable resources (Holt et al., 2012; Lelivelt et al., 2015). Additionally, biofabrication consumes less energy than existing manufacturing practices as it relies on the organism itself for the production. Also, the materials produced are biodegradable (animal leather is also biodegradable) and non-toxic, causing no harm to the environment. Lastly, their disposal at their end of life can nurture the cultivation of new materials (Jones et al., 2017; Jiang et al., 2013). Based on these advantages, biofabrication can be considered a reasonable approach to effective sustainable practices.

As with any developing technology there are challenges shared by all biofabrication approaches discussed by Mironov et al. First, biofabrication relies on the collaboration with different disciplines; therefore, having a highly motivated team and adequate facilities are vital. Second, access to living organisms is essential as well as tools for material and functional characterization and bioreactor-based monitoring. Without these laboratory needs, interruption of work could lead to other deficiencies. Third, research needs for biofabrication vary depending on the size of the group. For example, bigger groups might need access to expensive or advance equipment. Fourth, sterile and controlled environments are fundamental for the practice of biofabrication since contaminants could affect the work. Lastly, the potential to scale up and the cost-effectiveness of any biofabrication must be taken into consideration starting from the ideation phase to guarantee a good transition into its potential commercialization (Mironov et al., 2009).

Since biofabrication is an emerging technology, it is difficult to pinpoint the exact role of designers within this practice. What is possible to say is that their intervention and collaboration with other disciplines (e.g. biology, materials science, chemistry) (Miodownik, 2007) is advancing the creation of novel materials, products, and manufacturing processes from living organisms (Montalti, 2013; Ciuffi, 2013; Camere & Karana, 2017). Some examples come from Eric Klarenbeek and Maartje Dros with their bioplastic made from algae, BioMASON® with their bricks that use microorganisms to grow biocement™-based construction materials, and Natsai Chieza with her microbe-painted silks. There are also those not directly involved with the production of materials or products, but rather creating spaces for collaboration for design and science such as Amy Congdon's Biological Atelier and Suzanne Lee's Biocouture. Lee is also known for her work with bacterial cellulose. *Figure 4* shows a collection of works from the mentioned designers, artists, and companies. Examples of those biofabricating with fungi will be presented in the section *Biofabricating with Mycelium* of *Chapter 5*.

The above examples illustrate the attitude of this thesis. The interaction with experts to integrate disciplinary practice and knowledge at VTT, is a small step towards the development of biofabrication as an alternative to traditional manufacturing practices.

Eric Klarenbeek & Maartje Dros

Amy Congdon

BioMASON®

Suzanne Lee

Natsai Chieza

Figure 4. Examples of biofabrication.

2.3 FUNGAL LEATHER-LIKE MATERIALS: A SUSTAINABLE ALTERNATIVE TO ANIMAL LEATHER

Fungi are a taxonomic kingdom of their own, which is enormously diverse. It is estimated that there are possibly about 1.5 to 5 million species of fungi (Hawksworth & Lücking, 2017). Inspired by the diversity of this kingdom, leather-like materials from fungi are explored as an alternative material to animal leather.

More specifically, the part of fungi used in this research is mycelium. It is the vegetative part of a fungus composed of fine white filamentous structures called hyphae (Kavanagh, 2011). *Figure 5* illustrates the visual appearance of this living organism. All materials grown were guided and defined merely by genetic information and controlled culturing conditions. Genetically engineered organisms were not used. Biofabrication is practiced by merging design processes with the principles of biology related to fungal cultivation techniques.

As a clarification, the material explored is not leather. The term leather is reserved for animal hides which contain collagen. This work does not use collagen, but rather mycelium. The material exploration does not pretend to replace animal leather or synthetic leather, it is meant to widen the scope of material opportunities in the future by promoting the idea of an *alternative* material, whose production could be much more sustainable compared to the current options in the market.

Based on these grounds the following research questions were developed:

1. *What processes at the intersection of design and biology contribute to sustainable alternatives to animal leather?*
2. *How might this collaboration contribute to understanding the future work of designers in laboratories?*

Both questions are situated in the context of biodesign using some of the principles of speculative design. The first question is aimed at understanding the designer's practice in laboratories through biofabrication. The second question is intended to provide insights about the future work for designers in laboratories.

This research is, in its entirety, transdisciplinary (Muratovski, 2015) since the topic of fungal leather-like materials is studied by applying existing knowledge from design and learned knowledge from biology. Constructive Design Research is utilized as the research approach based on the proposed model by Bang et al. (2012). For the crafting of fungal leather-like materials, an adapted version of the Material Driven Design Method (MDD) by Karana et al. (2015) was employed. The adaptation consists of three steps focused on material experimentation, material analysis, and material prototypes. The process of biofabricating leather-like materials is the central axis of this research. Several stakeholders, including designers, scientists, and engineers were involved at different phases of the design process.

2.4 TERMINOLOGY

This research explores the emerging material practice of designing with living organisms, therefore, the following technical terms were defined to ease the reader with the content in later chapters.

Figure 5. Mycelium.

Colony: "A distinguishable localized population within a species" ("colony", 2019).

Control: "An experiment in which the subjects are treated as in a parallel experiment except for omission of the procedure or agent under test and which is used as a standard of comparison in judging experimental effects" ("control", 2019).

Culture: "The act or process of cultivating living material (such as bacteria or viruses) in prepared nutrient media" ("culture", 2019).

Experiment: "An operation or procedure carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis, or to illustrate a known law" ("experiment", 2019).

Media: "A nutrient system for the artificial cultivation of cells or organisms and especially bacteria" ("medium", 2019).

Mycelium: "The mass of interwoven filamentous hyphae that forms especially the vegetative portion of the thallus of a fungus and is often submerged in another [element]" ("mycelium", 2019).

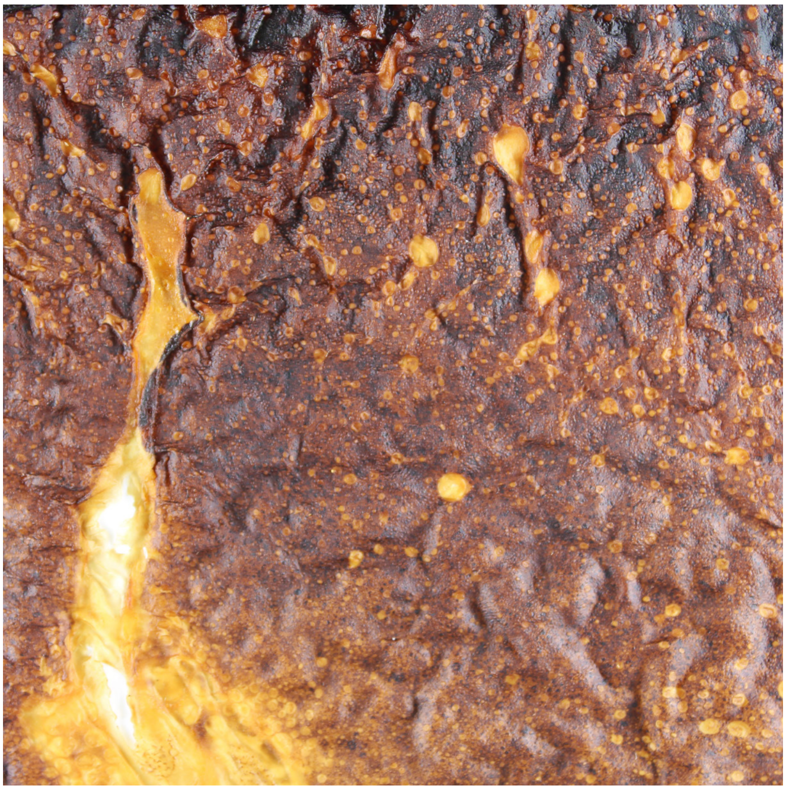
Species: "A category of biological classification ranking immediately below the genus or subgenus, comprising related organisms or populations potentially capable of interbreeding, and being designated by a binomial that consists of the name of a genus followed by a Latin or latinized uncapitalized noun or adjective agreeing grammatically with the genus name" ("species", 2019).

Sporulation: "Division into many small spores ("sporulation", 2019).

Strain: "A group of presumed common ancestry with clear-cut physiological but usually not morphological distinctions" ("strain", 2019).

Substrate: "The base on which an organism lives" ("substrate", 2019).

3: METHODOLOGY & STRUCTURE



3: METHODOLOGY & STRUCTURE

This chapter is composed of five sections aimed at describing the methodology and structure of this research. In the first section, I define the type of collaboration that took place as well as the structure of all theoretical and practical content. Next, the research approach of Constructive Design Research is introduced. Then, I cover the model of Constructive Design Research utilized in the context of fungal leather-like materials. After that, the Material Driven Design (MDD) method is presented. The chapter concludes with a detailed description of the adapted version of the MDD method and the three different steps created solely for the purpose of this research.

3.1 COLLABORATING AT THE INTERSECTION OF DESIGN AND BIOLOGY

Transdisciplinary collaboration is at the core of this research as it links design to biology. According to Lawrence and Després (2004) today's global issues, such as greenhouse gas emissions, water scarcity, or waste production are tackled from the perspective of different disciplines. Such is the case of this thesis, where new ways of working were adopted from biology to enable the collaboration and work across disciplines. It is important to note that models for conducting transdisciplinary research are still under construction (Muratovski, 2011). In fact, some literature might classify the work of this thesis as interdisciplinary, but under Muratovski's view, interdisciplinary collaboration does not take designers to *transcend* from their disciplinary norms and adopt those from other disciplines (2015).

All laboratory work was conducted at the premises of VTT Technical Research Centre of Finland, where services on research and innovation are the backbone of their work to address global challenges with a sustainability mindset. VTT functions under the command of the Ministry of Employment and the Economy.

Fitting both disciplines, design and biology, into one structure formed part of the challenge. Design was kept at the core of the investigation; however, demonstrating a sense of sensitivity and understanding towards biology was at all times necessary. For this reason, some sections include information belonging more closely to biology.

The theoretical framework of this thesis consists on biodesign and speculative design literature located in *Chapter 4: The Emerging Practices of Speculative Design and Biodesign*. The first two sections cover the significance of designing for alternate futures and the topic of speculative design. The other four sections cover the topic of biodesign, state the difference between natural and artificial materialities, describe the new wave of (bio)material designers, and conclude with defining a pathway for biodesign.

The practical work lies at the core of this research. It is enclosed in *Chapter 5: The Process of Biofabricating with Mycelium*, which is composed of six sections. The first section narrates my personal experience in the laboratory as a space for transdisciplinary collaboration. The narrative continues in the second section covering my experience in the laboratory as a space for material exploration. The third section defines and describes all the technical aspects related to mycelium. The fourth section, *Material Exploration: Understanding the Material in the Laboratory*, introduces the experiments and the material motivations for conducting each one of them. The fifth section *Material Analysis: Creating Material Experiences and Future Visions with Users*, exposes the data pertaining to the material experiences and future applications obtained in the workshops and interviews. The chapter concludes *Material Prototypes: Unfolding Alternate Material Futures*, where the three speculative case studies are revealed. *Figure 6* illustrates the timeline of the main research activities.

In the last chapter, *Chapter 6: Conclusion*, the validity of this research, its limitations, and considerations for the future are described.

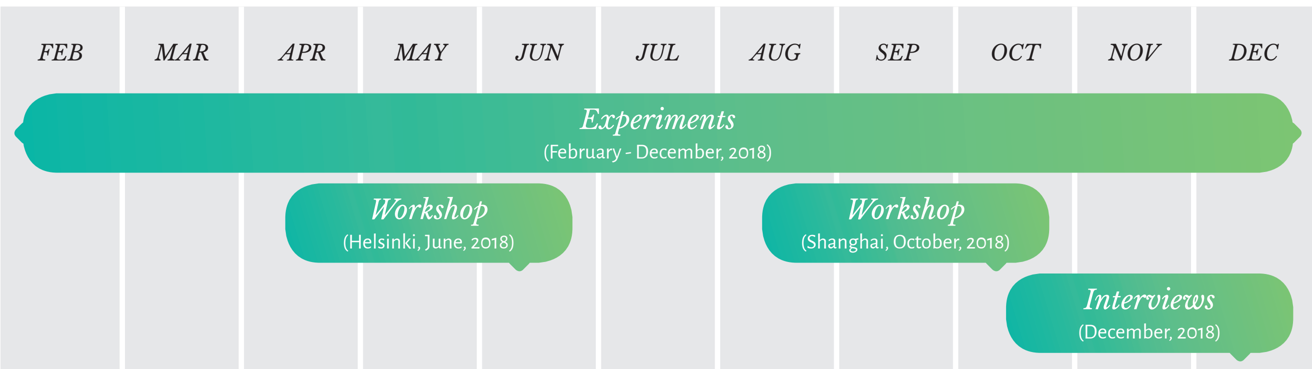


Figure 6. Timeline of research activities.

3.2 CONSTRUCTIVE DESIGN RESEARCH

The methodology of this research is engrained in the ideologies of Constructive Design Research, also known as *Research-through-Design*. This research approach offers methodological flexibility to produce knowledge by employing design know-how (Bang et al., 2012). Constructive Design Research is defined as "design research in which construction – be it product, system, space, or media – takes center place and becomes the key means in constructing knowledge" (Koskinen et al., 2011, p. 5).

When referring to Constructive Design Research, Koskinen et al., state that this research approach is mainly structured by three contexts: *the lab, field of study, and showroom* (2011). However, Bang et al. express that this research approach provides limited tools appropriate to managing and linking methods and techniques together beyond the contexts proposed by Koskinen et al. (2012). Since this investigation plays with different elements from design and biology, a model proposed by Bang et al. for conducting Constructive Design Research was utilized *(Figure 7)*.

Their model introduces *motivational contexts* under the impression that "motivations for both designing and researching can come from a number of sources" (Bang et al., 2012, p. 3). Additionally, the experiments for the creation of fungal leather-like materials have great significance and so do the hypotheses behind each one of them. In the model by Bang et al. (2012), experiments are situated at the central axis. This model provided a suitable structure to guide the entire design process, while easing the framing and reframing of all research activities.

The model proposed by Bangs et al. is formed of six main parts: *Motivation, hypothesis, experiment, research question, evaluation, and knowledge.* The model allows *hypotheses* to function as an on-going activity that is framed - and reframed - by a research *motivation*. However, the motivation must have a direct relevance to the experiments. The hypothesis progresses in a cycle-like process centered around the *experiments* and feeds the *research question*. The framing and reframing of the *research question* can be stimulated by pure experimentation without having a clear aim or strategy (Zimmerman & Forlizzi, 2008) – this was the case with the exploration of leather-like materials. After obtaining a hypothesis based on a clear motivation, the research question eventually produces criteria for *evaluation*. *Knowledge*, the ultimate goal, is achieved after careful evaluation. Nonetheless, given their centrality, the experiments, can modify – or be modified by – the other areas. This means that experiments can also generate knowledge in the form of artifacts or experimental design proposals (Bang et al., 2012).

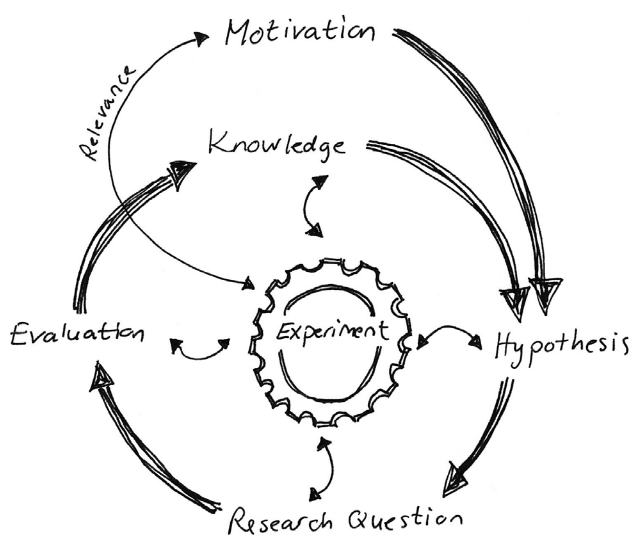


Figure 7. Constructive Design Research model. Reprinted from "The Role of Hypothesis in Constructive Design Research," by A. L. Bang, P. G. Krogh, M. Ludvigsen, & T. Markussen, 2012, *Kolding School of Design*, p. 6. Copyright 2012 by Kolding School of Design. Reprinted with permission.

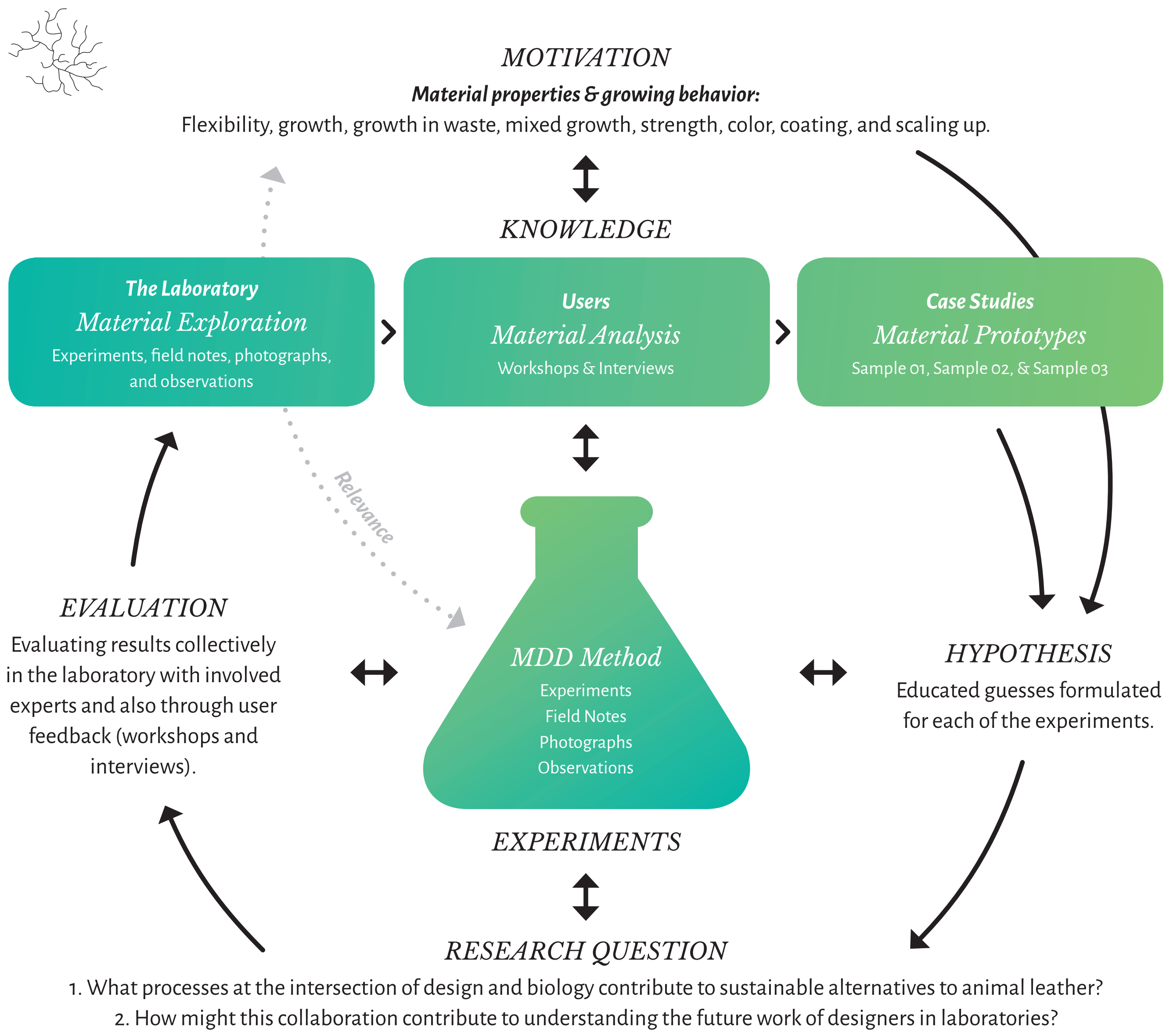


Figure 8. Constructive Design Research model in the context of fungal leather-like materials. Adapted from "The Role of Hypothesis in Constructive Design Research," by A. L. Bang, P. G. Krogh, M. Ludvigsen, & T. Markussen, 2012, *Kolding School of Design*, p. 6. Copyright 2012 by Kolding School of Design. Adapted with permission.

3.3 CONSTRUCTIVE DESIGN RESEARCH MODEL IN THE CONTEXT OF FUNGAL LEATHER-LIKE MATERIALS

Understanding the Constructive Design Research model by Bang et al. (2012) is fundamental in this work. For this reason, the design process and all the research activities elaborated are placed into perspective in *Figure 8*.

As the model implies, experiments have a leading role in this investigation. These experiments were conducted and guided using an adaptation of the MDD method (Karana et al., 2015). The MDD method is explained in the following section.

In the context of fungal-leather like materials, every *hypothesis* derived from a *motivation* inspired by specific material properties (mechanical) and the growing behavior of fungal species. These hypotheses helped to nurture and advance the main *research question*. Furthermore, the *evaluation* of the experiments was done collectively in the laboratory with the experts involved and through user feedback (workshops and interviews). The *knowledge* created comes from three main areas. The first one is the material exploration composed of experiments, field notes, photographs, and observations as research tools. The second one is the material analysis composed of two workshops and ten interviews. The third one is the material prototypes composed of three final samples used as case studies to expose the speculation of the material. These three steps of the research are discussed in detail in *Chapter 5: The Process of Biofabricating with Mycelium*.

3.4 MATERIAL DRIVEN DESIGN (MDD)

While the model by Bang et al. (2012) provides direction to the different parts of this research, the MDD method is used to guide the design process of all the experiments. This method is unique as it sets materials at the beginning of the design process to define and design for material experiences in circumstances where a material is the main driver (Karana, 2014). Additionally, as Karana et al. state, the MDD method is a good alternative "when designing with a *material proposal* with semi-developed or exploratory samples (e.g. food waste composites, living materials made of bacterial cells, 3D printed textiles, flexible OLEDs, etc.)" (2015, p. 39). Even though the MDD method still possesses areas for improvement and further research, it offered the methodological flexibility needed to conduct this investigation (Karana et al., 2015).

In this work, material samples were crafted from the very beginning of the design process to broaden understanding of the material properties, future applications, and stimulate the creation of material experiences. The aim was not to develop perfectly finished products, but rather to produce rough material prototypes. In this respect, the method was extremely valuable as it turns around the traditional design process. Instead of beginning the design process by solving a problem and defining material requirements; the method starts with a given material or set of materials to discover its opportunities. Unlike problems, functions, or forms; materials themselves are the starting point of the design process (Karana, 2014). In the context of this research, fungal leather-like materials are used as prototypes to evoke questions and reflect on the implications of design decisions we make today, and how they may progress into the future – *speculative design*.

The MDD method is composed of four action steps identified as: 1) Understanding the material, 2) Creating Materials Experience Vision, 3) Manifesting the materials experience patterns, and 4) Designing the material/product concept *(Figure 9)*. Adaptation of the method is allowed. The method is not exclusive to one single chronological usage. The author, Elvin Karana, explains that upon the completion of *Step 1*, the designer might understand the material to the extent where he or she might have possible ideas for its application, where unique technical properties and experiential qualities of a material are incorporated or come forward. If this is the case, the designer can opt to proceed to *Step 4*, where material/design concepts are generated. However, if the designer prefers to explore beyond what is known and dive outside their own experiences to push their creativity towards new applications, then they can proceed to *Step 2* of the MDD method. Alternatively, if the designer is eager to express particular meanings of the material in the final application, *Step 3* is recommended as this is where patterns to create these meanings are manifested (Karana et al., 2015).

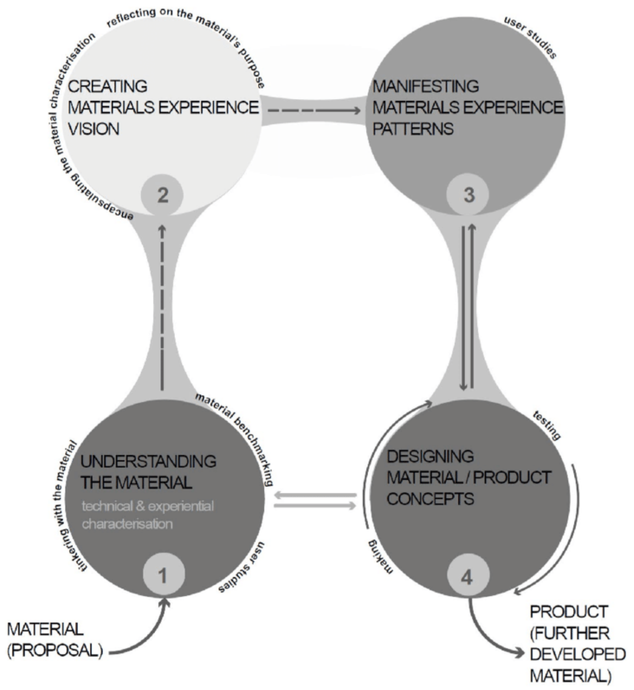


Figure 9. Material Driven Design (MDD) method. Reprinted from "Material Driven Design (MDD): A Method to Design for Material Experiences," by E. Karana, B. Barati, V. Rognoli, & A. Zeeuw van der Laan, 2015, *International Journal of Design*, 9(2), 35-54 (p. 40). Copyright 2015 by International Journal of Design. Reprinted with permission.

3.5 ADAPTATION OF THE MDD METHOD FOR FUNGAL LEATHER-LIKE MATERIALS

For the effect of this research, the MDD method was adapted and the process is illustrated in *Figure 10*. *Step 1 (Understanding the material)* is labelled ***Step 1 (Material Exploration: Understanding the Material in the Laboratory).*** *Step 2 (Creating Materials Experience Vision)* and *Step 3 (Manifesting the materials experience patterns)* were merged into one step called ***Step 2 (Material Analysis: Creating Material Experiences and Future Visions with Users).*** *Step 4 (Designing the material/product concept)* is identified as ***Step 3 (Material Prototypes: Unfolding Alternate Material Futures).***

In the adapted version, *Step 2* works in a bidirectional fashion with *Step 3*, so does *Step 3* with *Step 1* and *Step 2*. In the case of *Step 1*, this one is unidirectional with *Step 2*. Moreover, *Step 3* has an ongoing process where *making* and *testing* help to improve the materials (prototypes). In contrast to the original model, the materials or prototypes are not released for commercialization since the purpose of this research is speculative. Each *Step* is composed of different parts, discussed next.

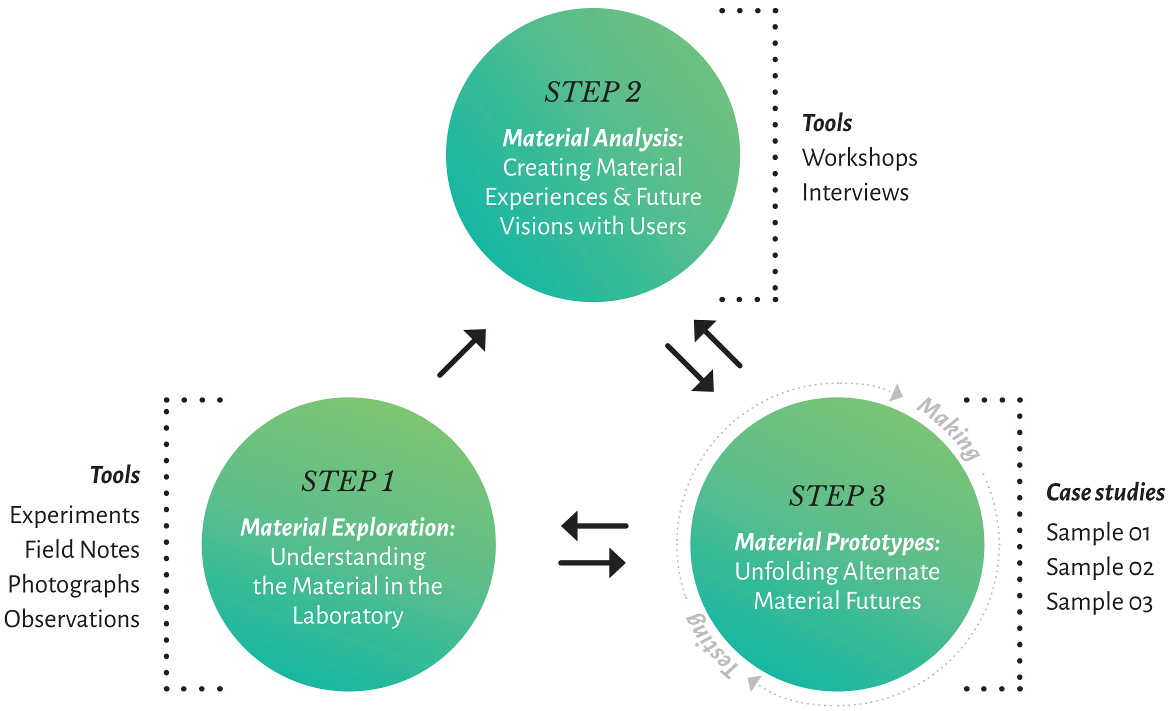


Figure 10. Adaptation of the Material Driven Design (MDD) method in the context of this research. Adapted from "Material Driven Design (MDD): A Method to Design for Material Experiences," by E. Karana, B. Barati, V. Rognoli, & A. Zeeuw van der Laan, 2015, *International Journal of Design*, 9(2), 35-54 (p. 40). Copyright 2015 by International Journal of Design. Adapted with permission.

3.5.1 Step 1 / Material Exploration: Understanding the Material in the Laboratory

In this section I define the tools used in the material exploration for data collection. These qualitative tools include experiments, field notes, photographs, and observations. Only the data from the experiments was analyzed. The material exploration was conducted as a non-linear process, meaning that all of the different tools were used interchangeably as new insights were obtained.

3.5.1.1 Experiments

The experiments are the core scientific method I learned and applied throughout my design process to comprehend fungi's agency. These experiments allowed me to explore the material properties and growing behavior of fungi as a leather-like material. Given the large number of experiments carried out, only those with the most compelling results were included in this document.

All information pertaining to the experiments was carefully recorded (date, species, media, amounts, procedure, and results). Based on the Constructive Design Research model by Bang et al. (2012), each experiment was driven by a motivation in the context of material properties (mechanical) and growing behavior. These motivations were the material's *flexibility*, *growth*, *growth in waste*, *mixed growth*, *strength*, *color*, *coating* and *scaling up.* These experiments are explained in detail in *Chapter 5: The Process of Biofabricating with Mycelium*.

For the analysis of results, controls were utilized. This means that for every experiment, two or more situations were observed. One of them was observed without any interference, while the others were manipulated in some way (Egler,

Figure 11. Material before drying *(B. robillardoides)*.

Figure 12. Writing down results in the lab notebook.

1970). This facilitated the comparison of results by qualitatively assessing their appearance, feel, and uniformity to draw conclusions and reframe the hypothesis, if needed, after each experiment.

3.5.1.2 Field Notes

The field notes I used included a confidential lab notebook and another notebook devoted to notes and sketches. They were used as qualitative documents for registering data before, during, and after each experiment (Creswell, 1994).

The lab notebook was another method I applied from biology. It is compulsory for everyone conducting laboratory work and allowed me to keep a chronological record of the experiments I conducted. All procedures, reagents, data, scientific interpretations, and hypotheses were included with the aim to record all data, draw conclusions, and make possible replications, if needed – crucial steps in any given scientific method, which differs from design methods, where the replication of any given outcome is not required nor expected.

The other notebook was more informal. It provided creative freedom and an outlet to more designerly ways of working. In this notebook, I included notes and sketches with the aim to build a diary with daily occurrences, thoughts related to the process, new ideas, challenges, aspects related to the cooperation with scientists, as well as potential applications for the materials.

3.5.1.3 Photographs

Throughout my research journey, I kept a photo diary to document the process behind every experiment (Creswell, 1994). These photographs were an important part of this research as they are the visual proof of all the main findings and they facilitated the reflection and comparison of all experimentation. Since all materials produced were 100% organic, some of them changed over time, while others also were damaged during the workshops, interviews, or talks with people.

3.5.1.4 Observations

Observations were applied when working in the laboratory and handling fungi. It was crucial for me to learn and apply, through observation and practice, the right protocol when working in a laboratory and conducting experiments (Koskinen et al., 2011). Scientific environments are much more controlled when compared to design environments due to the delicate nature of the work that happens in them, especially when dealing with living organisms. Therefore, I had to familiarize myself with a series of safety procedures, tools, equipment, and working processes.

Observation played also an important role in the adaptation of scientific language (Koskinen et al., 2011). For example, words like *culture, control* or *strain*, which can have different connotations in the context of design or other disciplines, became part of my daily vocabulary. Learning this new language (at a very basic level) was an essential part of this research. It gave me the opportunity to be understood among scientists. It was all learned by observing, repeating, and asking the meaning when lost in translation.

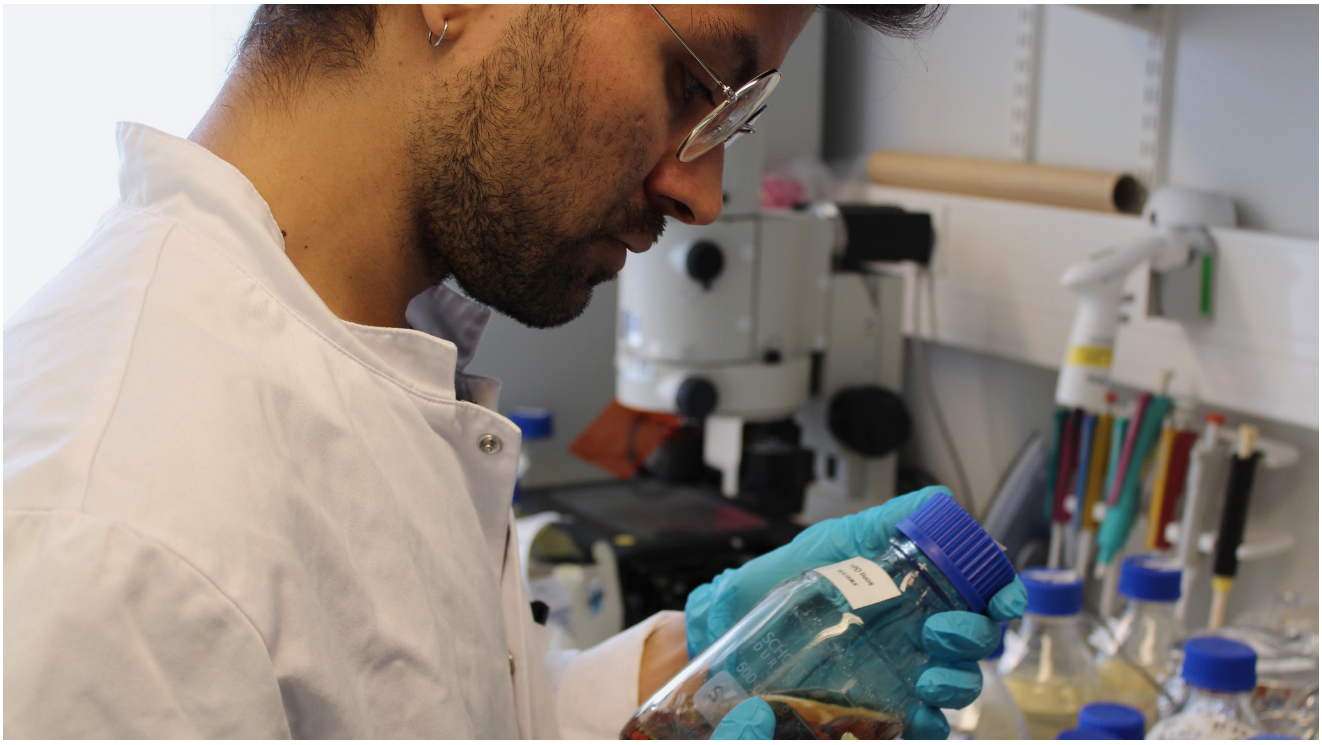


Figure 13. Checking the media before conducting an experiment.

3.5.2 Step 2 / Material Analysis: Creating Material Experiences and Future Visions with Users

In this section, I introduce the qualitative tools used for analyzing the material samples. I used these tools to summarize the main findings from the material exploration under a cohesive whole and reflect on the materials using user feedback. The purpose of the workshops was to explore the sensorial qualities of the material samples developed in *Step 1* and to create a future vision for the application of the selected material by the participants. The interviews were done to identify and define clearly the experiential qualities of the materials selected in the workshops and future visions related to potential applications.

3.5.2.1 Workshops

Two 3-hour long workshops were held. These ideation workshops were based on the principles of co-creation by IDEO (Rill & Hämäläinen, 2018) and future studies (Lauttamäki, 2014). My aim with these workshops was to invite users to explore the sensorial qualities and future applications using a selection of samples from the material exploration. These workshops were crucial as the brainstorming elaborated by the participants allowed the pre-selection of materials for further research.

The first workshop took place on June 17th, 2018 in Helsinki. It was composed of designers with previous knowledge in bio-based materials or textiles as well as experts coming from the fields of design, science, and engineering from Aalto University and VTT. Eighteen people participated in this workshop and three groups of six people each were formed.

The second workshop took place on October 30th, 2018 in Shanghai. This time the participants were twelve fashion design students from Shanghai International College of Fashion and Innovation (SCF) at Donghua University. Two groups of six people each were formed during this second workshop.

Qualitative data collected from the questionnaires, audios, videos, and notes taken during the workshops were written into single data form. The data was then reduced and separated into the groups formed at each workshop with their final selected sample. It was analyzed using content analysis (Krippendorff, 2018). Data was first coded by the words used to describe the materials. Second, patterns were identified such as the repetition of words among groups. Lastly, the data was interpreted to create an overall census.

The results of the workshop are explained in *Chapter 5: The Process of Biofabricating with Mycelium*. The printed materials used in the workshops are found in the *Appendix (section 2 and 3)*.

Figure 14. Participants during the workshop in Helsinki, Finland.

Figure 15. Participants during the workshop in Shanghai, China.

3.5.2.2 Interviews

Ten 30-minute long open-ended interviews (Creswell, 1994) were conducted during the month of December 2018 to a wide range of people coming from various backgrounds, nationalities, and ages. My aim with these interviews was to use the pre-selected samples from the workshops to explore further with users the material experiences at four experiential levels and to speculate in more depth about their future applications. These four experiential levels were: *sensorial*, *interpretive, affective,* and *performative* (Karana et al., 2015). They will be described in *Material Analysis: Creating Material Experiences and Future Visions with Users* of *Chapter 5*.

The data collected from the interviews was transcribed into single data form. It was analyzed in a similar manner to the workshops using content analysis (Krippendorff, 2018). In this case, the content was divided into the three samples given to each interviewee. Data was first coded by the words used to describe the materials, then patterns were recognized such as the repetition of words to describe the materials, and then data was interpreted to create an overview of each sample.

The results of the interviews are explained in *Chapter 5: The Process of Biofabricating with Mycelium*. The questionnaire used for the interviews are found in the *Appendix (section 4)*.

Figure 16. Conducting one of the interviews to gather information about the material's experiences.

3.5.3 Step 3 / Material Prototypes: Unfolding Alternate Material Futures

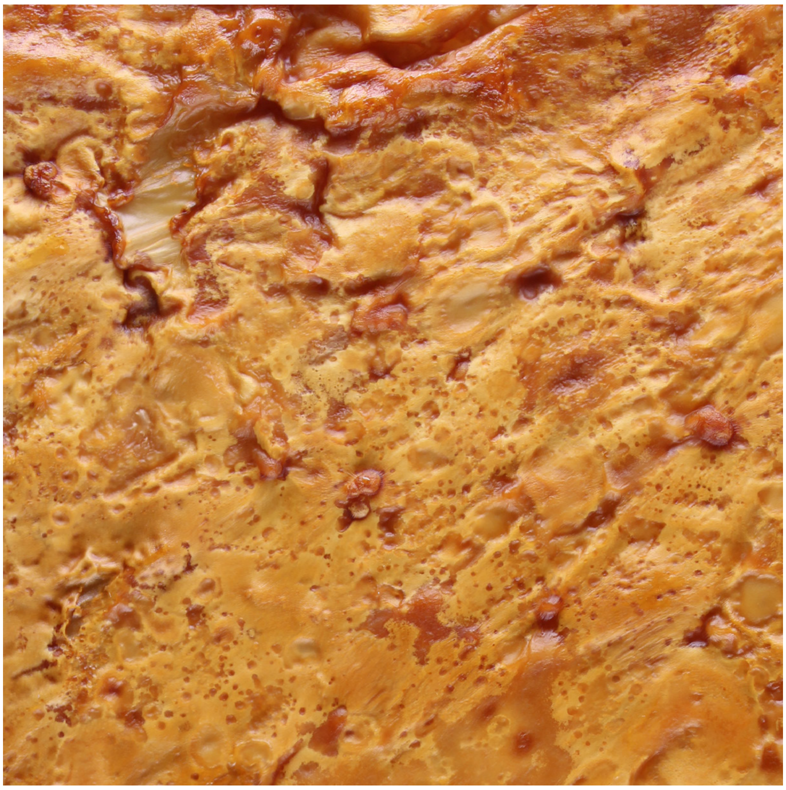
The three case studies in this section are the medium to speculate about the future uses of the selected samples using the main findings from the previous steps. They are labeled as *Sample 01 (P. chrysosporium)*, *Sample 02 (B. robillardoides – Version 1)*, and *Sample 03 (B. robillardoides – Version 2)*.

As Malpass states, "a common approach in techno-centric domains is for the designer and technologist to focus on what technology can do, and they often ignore the contextual factors" (Malpass, 2017, p. 56). Therefore, I wanted to use the ideologies of speculative design to widen the scope of what the technology of biofabrication can do in the future if we opt for alternative materials like those derived from fungi. My aim is to evoke users to wonder *why* we should adopt these types of manufacturing practices in relation to existing ones (e.g. animal leather production) or *what if* - in terms of the potential applications and implications of their growing properties - these living organisms are applied in biofabrication.

The speculative data and images pertaining to these case studies are described in detail in *Material Prototypes: Unfolding Alternate Material Futures* of *Chapter 5*.

Figure 17. Material sample *(B. robillardoides)*.

4: THE EMERGING PRACTICES OF SPECULATIVE DESIGN & BIODESIGN



4: THE EMERGING PRACTICES OF SPECULATIVE DESIGN & BIODESIGN

In this chapter, I introduce the emerging practices of speculative design and biodesign. First, I cover the use of futures and their classification within the concept of the futures cone in *Designing for Alternate Futures*. Second, in *Design Meets Speculation*, I present the topic of speculative design and its main principles.

The third section, *Design Meets Biology*, introduces the topic of biodesign. Fourth, I discuss briefly the differences between what is natural and what is artificial in *An Artificial Natural Future*. Fifth, in *A New Wave of (Bio)Material Designers*, I review the emerging practice of grown materials and the role of designers in this context**.** Lastly, the chapter concludes by looking at existing pathways for designers practicing biodesign in the section *Defining a Pathway for Biodesign*.

The views expressed here come from the review of selected literature from some of the most prominent authors on the topic of speculative design and biodesign. It is crucial to understand that both, speculative design and biodesign, are not practices with set methods, processes, and tools as other more grounded design practices. They were selected since my work comes under the umbrella of biodesign, but since the material I biofabricated with is not fully developed, creating future alternatives was necessary; therefore, some of the principles of speculative design are applied.

To allow a good narrative, speculative design is discussed first since the introduction to biodesign leads to the chapter on the process of biofabricating with fungi.

4.1 DESIGNING FOR ALTERNATE FUTURES

Images of the future have prevailed in societies for many years. These images, for the most part, "depict an essentially stable order of society, often containing the ideas of perfection and/or sustainability" (Morgan, 2015, p. 109), but we must consider all kinds of futures – the ones we want and those we do not want. To explore these alternative futures and move away from the common association of design as a *perfect* problem-solving tool, this thesis looks at biofabrication through the lens of *speculative design*, interested in evoking questions and creating debate, rather than proposing one final solution.

In order to understand better the topic of speculative design, the *futures cone* proposed by Anthony Dunne and Fiona Raby (2013) are used as reference to set the context for the future vision of this research. The taxonomy of the different types of futures placed into a cone was initially explored by Hancock and Bezold (1994), who based their cone on the taxonomy of futures by Henchey (1978). Since then, many scholars and futurists have made variations of it (Voros, 2017). The futures cone by Dunne and Raby is appropriate for this research as their theoretical groundings are directly linked to design. Furthermore, they are leading pioneers of critical design, which incorporates speculative design as one of their practices (2013). In the futures cone by Dunne and Raby, futures are classified as probable, plausible, possible and preferable *(Figure 18)*.

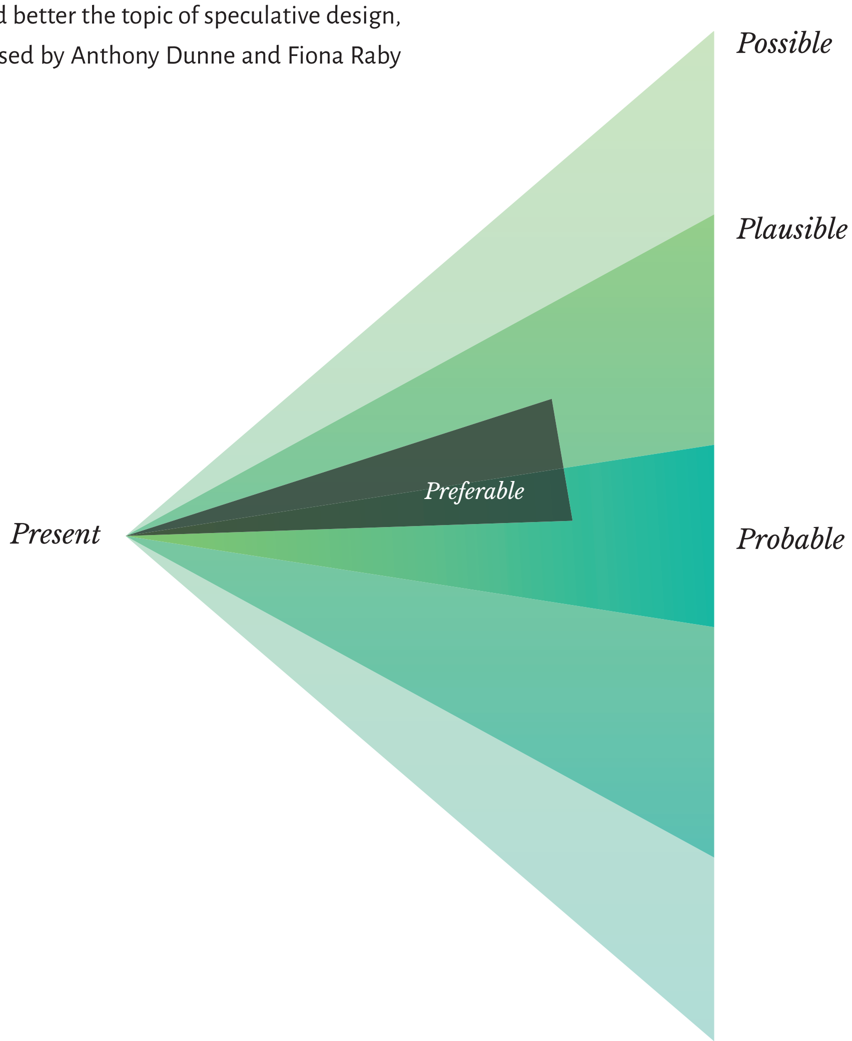


Figure 18. Futures cone. Adapted from *Speculative everything: Design, fiction, and social dreaming* (p. 5), by A. Dunne & F. Raby, 2013, Cambridge, Massachusetts: The MIT Press. Copyright 2013 by Massachusetts Institute of Technology. Adapted with permission.

The first cone is the *probable future*. These are futures that we consider are *likely* to happen based on existing information, unless an unexpected event takes place such as war or natural disaster. For the most part, the discipline of design is located here (e.g. design methods, processes, tools, design education, etc.) since many designs act as a medium to evaluate these probable futures (Dunne & Raby, 2013).

The second cone is the *preferable future*, located between the probable and plausible futures. This future is concerned with what we consider *should or needs* to happen. This future is determined using value judgments coming from entities including the government and industry (Kolehmainen, 2016). Conflicts of interest could take place here due to power relations. In this future context, people act as voters or consumers, but yet the influence is limited (Dunne & Raby, 2013).

Next is the *plausible future*. This future relies on existing knowledge, for example physical laws, processes, causation, systems of human interaction, etc. (Voros, 2001). This future is less about prediction and more about planning and foreseeing to ensure resilience in a diverse number of futures (Dunne & Raby, 2013).

The last cone is *possible futures*. Here the present and a suggested future are interlinked to propose futures that *might* happen. It is within this future where speculative design takes place (Dunne & Raby, 2013). Voros credits *possible futures* as those reliant on knowledge that is not yet available (2001). This is to some extent true as this thesis uses existing design and biology knowledge to practice biofabrication with certain limitations since the technology is not yet fully developed, nor the material. Nevertheless, the aim is to drive material exploration towards the construction of a future that *migh*t happen for fungal leather-like materials.

Furthermore, it was observed how future visions can emerge as a response to other futures within the futures cone. This is an area not fully explored by the research community and one where this work could provide useful knowledge. For example, the *possible future* promoted in this research acts as a response to the *plausible future* grounded on the theory of planetary boundaries. This theory dictates a *safe operating space* for humans due to our increasing interference with the Earth system and natural laws (Steffen et al., 2015). Some of its criticism is that planetary boundaries "do not dictate how human societies should develop but they can aid decision-makers by defining a safe operating space for humanity" (Richardson, n.d.). In this sense, the construction of a *possible – speculative - future* is one way to dictate sustainable development in human societies and inside industries such as the animal leather industry.

As discussed in *Chapter 2*, the animal leather industry has several sustainability challenges which are directly linked to all planetary boundaries. Data analyzing each boundary in relation to animal leather production is not fully available, but since the leather and fashion industry possess great environmental impact, the graphs published in *The Pulse of the Fashion Industry 2017* are included to exemplify this reasoning (Global Fashion Agenda & The Boston Consulting Group, 2017). The graphs depict the planetary boundaries as of 2015 *(Figure 19)* and those of 2030 if no actions are taken *(Figure 20)*.

Planetary boundary

Distance from planetary boundary

Energy emissions

Land use

Water consumption

Chemicals usage

Waste creation

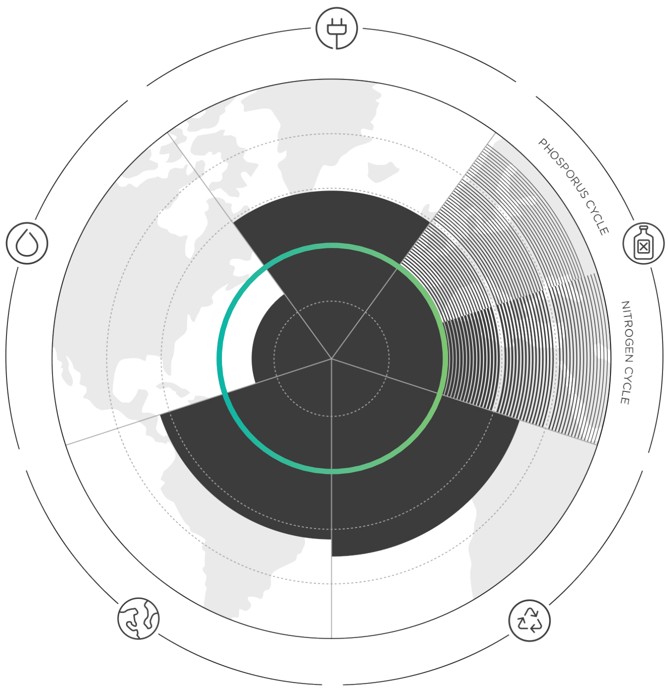


Figure 19. The Planetary Boundaries 2015 (Planetary boundaries have already been breached). Reprinted from *Pulse of the Fashion Industry* (p. 9), by Global Fashion Agenda & The Boston Consulting Group, 2017, Retrieved April 7, 2019 from https://static1.squarespace.com/static/5810348d59cc68e529b7d9ba/t/596454f715d5db35061ea63e/1499747644232/Pulse-of-the-Fashion-Industry_2017.pdf. Copyright 2017 by Global Fashion Agenda and The Boston Consulting Group, Inc. Reprinted with permission.

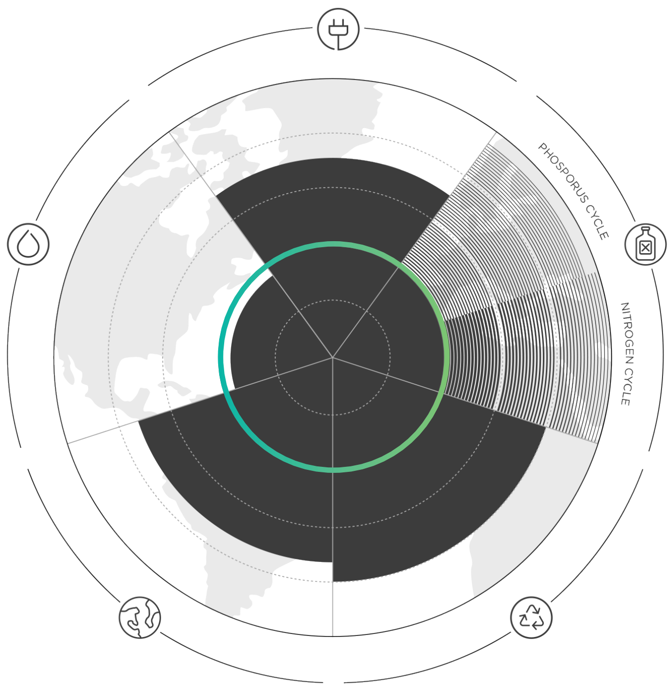


Figure 20. The Planetary Boundaries 2030 (Planetary boundaries will be even further exceeded). Reprinted from Pulse of the Fashion Industry (p. 9), by Global Fashion Agenda & The Boston Consulting Group, 2017, Retrieved April 7, 2019 from https://static1.squarespace.com/static/5810348d59cc68e529b7d9ba/t/596454f715d5db35061ea63e/1499747644232/Pulse-of-the-Fashion-Industry_2017.pdf. Copyright 2017 by Global Fashion Agenda and The Boston Consulting Group, Inc. Reprinted with permission.

4.2 DESIGN MEETS SPECULATION

Designing for the future is a fairly new phenomena grounded on the principles of critical design (Dunne & Raby, 2001). This practice was developed by Anthony Dune and Fiona Raby in the mid-nineties during their research years in the Computer Related Design studio at Royal College of Arts in London (Dunne & Raby, 2013). Although, some literature appoints its beginnings to the design collective Droog during their 1993 Milan exhibition (Malpass, 2017). The term *Critical Design* was officially introduced in *The Pillow: Artist Designers in the Digital Age* (Dunne & Gaver, 1997).

Critical design emerges from the need to make an intellectual stance for the discipline of design. In contrast to traditional design practice, critical design is disinterested in commercialization or having a direct physical use. Otherwise, as Dunne and Raby uphold, the practice would "lose all intellectual credibility and viewed simply as an agent of capitalism" (Dunne & Raby, 2001, p. 59). For Dunne and Raby, "critical design uses speculative design proposals to challenge narrow assumptions, preconceptions, and givens about the role products play in everyday life" (2013, pg. 34). This definition sets a new critical paradigm for design, but other scholars like Graham Pullin, stress the fact that the definition falls short as it views critical design only by its practitioners; leaving out those critical designers who view it by its observers (Malpass, 2013). Other authors such as Mazé and Redstöm, point out that a common aspect practiced by all critical designers is the need to use design as a medium to diversify, rather than simplify the meanings behind design solutions and ideas (2007). It would be rather naïve to encapsulate critical design practice into a single definition given the different directions it has taken up in recent years, yet Matt Malpass offers three different routes to understand critical design as of today: *associative design*, *critical design*, and *speculative design* (Malpass, 2013).

Figure 21. 100 Chairs in 100 Days (2013).

Figure 22. Blood/Meat Energy Future. *Is this Your Future?* (2005).

Associative design creates a narrative using objects as the critical medium from which values and traditions of the design practice are exposed for criticism, linking it more towards artistic discourse rather than design for production (Malpass, 2017). A good example is Martino Gamper's *100 Chairs in 100 Days* (2013) where design is used as a vehicle through which the author critiques the obsolescence of objects using a chair as discourse *(Figure 21)*. On the other hand, critical design is interested in critical social theory and critiques the social, cultural, and ethical structures found in our present (Malpass, 2017). An example of this practice is Dunne and Raby's *Is this Your Future?* (2005). In that work *(Figure 22)*, the authors examine the future uses of energy from a social, cultural, and ethical perspective using different artifacts and built scenarios (Malpass, 2017). Both associative design and critical design have a deeper theoretical foundation, but more coverage and significance are given to speculative design discussed next.

What makes speculative design different from the other two is that it functions within a techno-scientific domain (e.g. biotechnology, nanotechnology, synthetic biology, artificial intelligence, etc.), while articulating the potential of ambiguity within the design discourse (Malpass, 2013). This transdisciplinary practice is not interested in utopic or dystopic images of the future as widely discussed in literature by authors like Dennis Morgan when referring to the idea of progress (2015). Instead, speculative design takes those utopian and dystopian images to construct assumptions and questions about adopting a new technology and the role of design in providing that technology. The aim is to make perceptible to users scientific data and highlight the cultural and social implications of techno-scientific environments (Malpass, 2016).

As Matt Malpass explains, speculative design work has two main functions. First, it makes technology tangible by delivering prototypes or scenarios to imagine how a certain technology could be applied in the near future. Second, it allows the reflection of present technology by creating possible future uses and examining progress through different pathways (2016). The practice allows those working in techno-scientific environments to focus on the contextual factors of a technology today and in the future, rather than what technology can do. As Auger argues, nowadays technology is functioning at more complex levels (e.g. biotechnology, Internet of Things, artificial intelligence, etc.) where the decoupling of design from its commercial approaches and traditional design practices can lead to making design decisions based on questions and public discourse rather than capitalistic viewpoints (2013).

Based on the reviewed literature, the methods and techniques to apply speculative design still need further development and clarification. Nevertheless, Dunne and Raby (2013) and Matt Malpass (2017) have pin-pointed some pathways and commonalities for practicing speculative design. The first is the use of design as a vehicle for questioning. Second, positioning objects for discursive purposes rather than for commercial utility (para-functionality). Third, supporting the objects used for speculation with a narrative, this is particularly important as some objects and their environments might feel too foreign and the association with the present could be lost. Forth, using ambiguity to exalt unusualness and trigger the act of questioning. Lastly, using satire through the techniques of exaggeration, distortion, and allegory (Malpass, 2013; Dunne & Raby, 2013, Gaver, W. et al., 2003).

Figure 23. The Dreamer. *Evidence Dolls* (2005).

Some examples of speculative design include the works of Dunne and Raby, Auger-Loizeau, and Tobie Kerrige and Nikki Scott in collaboration with Ian Thompson. In *Evidence Dolls* (2005), Dunne and Raby use young women as their audience to explore how genetic technology will change the way we date compared to today's dating rituals *(Figure 23)*. Other speculative work by the same authors include *Between Reality and the Impossible* (2010). In this piece, they use techniques of distortion to speculate about the effects of overpopulation by taking the controlled environment of a laboratory to the fields *(Figure 24)*. On the other hand, in *Smell+* (2009), commissioned by Phillips, Auger-Loizeau, explores the experience of the sense of smell while applying scientific know-how *(Figure 25)*. Lastly, in *Biojewellery* (2003), designers Tobie Kerrige and Nikki Scott, and bioengineer Ian Thompson, explored using bone tissue culturing to create two wedding rings. This sets a new tone for the traditional symbols used for human engagement *(Figure 26)*.

Based on the reviewed literature, it was inferred that the theories, methods, and techniques of speculative design are a work in progress. It is under that impression that this work is conceived. It sees speculative design as "more of an attitude than anything else, a position rather than a methodology" (Dunne & Raby, 2013, p. 34) to stimulate critique into the work conducted in laboratories when handling new technologies such as biofabrication. Through speculation, my stance is that designers can advance scientific research by evoking questions, rather than final solutions (e.g. products). Speculative design invites practitioners and users to consider how a current technology – such as the biofabrication of leather-like materials from fungi - could be applied in the future and the implications of opting for that technology today and in the future. Making technology perceptible to users is crucial as we can shape it based on their social, cultural, and ethical needs.

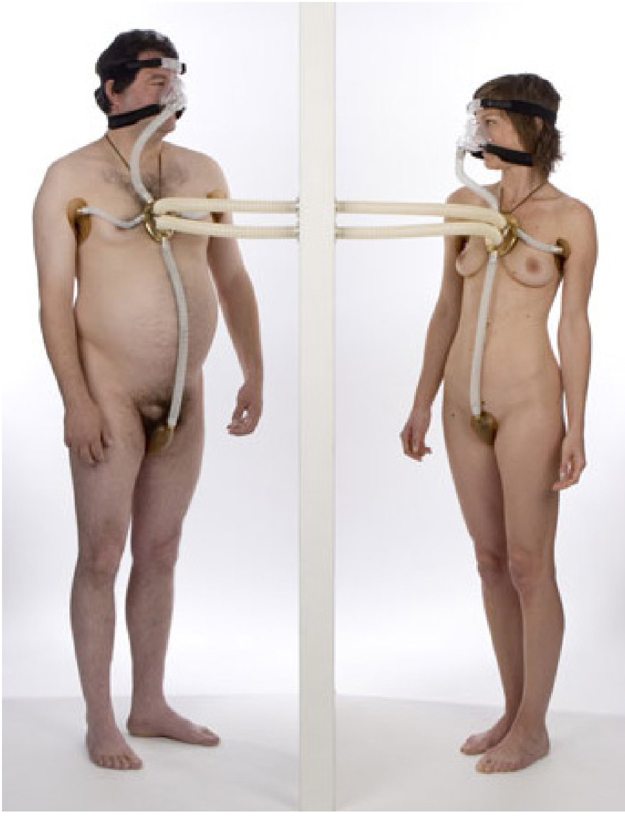


Figure 25. Smell+ (2009).

Figure 26. Biojewellery (2003).

Figure 24. Foragers 2. *Between Reality and the Impossible* (2010).

4.3 DESIGN MEETS BIOLOGY

It has been studied and predicted that the effect of existing human activities have on the environment hold serious implications as those expressed earlier by the planetary boundaries in *section 4.1* (Steffen et al., 2015). From the growing urgency to protect life on the planet appears *biodesign*. This emerging design practice is interested in exploring new ways to integrate living entities, whether they are cells or cultured tissues, into our daily interaction with products and services (Myers, 2012).

In a similar fashion to speculative design, biodesign takes place in a techno-scientific domain. However, in biodesign the aspect of the future is not necessarily studied and living matter is the focus for design research and production. This transdisciplinary practice is specifically interested in "the incorporation of living organisms as essential components, enhancing the function of the finished work" (Myers, 2012, p. 8). This practice takes into account fields interested in the integration of life such as biofabrication and synthetic biology. To some extent, these fields can be clustered into the field of biotechnology as discussed in *Chapter 2: Background*.

Biodesign is a field whose practices are not yet well defined. For example, in existing literature some scholars utilize the term *Growing Design* (Karana & Camere, 2018) as a more designerly way to refer to biofabrication, which could create some confusion among collaborators (e.g. designers and biologists). On the other hand, William Myers's book *BIODESIGN: nature, science, creativity* was considered to offer clear and neutral views on this emerging practice. In addition, other literature like *Synthetic Aesthetics: Investigating Synthetic Biology's Designs on Nature* by Ginsberg et al. (2014) offer a good analysis on biodesign, but only from the perspective of synthetic biology. Other books cover the topic from a medical standpoint such as *Biodesign: The Process of Innovating Medical Technologies* by Yock et al. (2009). Lastly, there are also numerous scholarly publications covering the topic of biodesign while referring to specific cases and uses, but most are rather scientific and not within the language of the design community. These claims are essential to this research since it was found that it is not yet possible to set the parameters for this evolving practice. However, the fact that biology is obtaining an important role in design is clear.

New forms of adaptation, productivity, and cooperation with nature are developing. The relevance of biodesign exists in exploring possibilities beyond "growing structures with trees or integrating objects with algae bioreactors" (Myers, 2012, p. 10). It employs technologies like biofabrication as tools to co-create systems using nature. Thus, in the context of biodesign, one can agree with Fabrizio Ceschin and Idil Gaziulusoy who suggest that sustainability should be understood as "a system property and not a property of individual elements of systems" (2016, p. 119) since biodesign is driven by sustainability. To make the practice beneficial, innovation should derive from the relationships among systems, rather than their isolation (Bertalanffy, 1967). For instance, designers should look into changing feedback loops or adapting the dynamics of interaction among systems in a regenerative manner (Mononen, 2017). Furthermore, our interests with biodesign should be driven by targets or visions and not by the conventional goal-driven tactics (Ceschin & Gaziulusoy, 2016). In this sense, speculative design could become useful as the practice develops further.

Examples of designers creating biological materialities include the work of Carole Collet with her project *Biolace* where she envisions plants as manufacturing entities that could grow food and textiles in the future *(Figure 27)*. Companies like Philips Design, have also brought biodesign into their work in projects like *Microbial Home* where they use home waste streams from one area to feed another, thus creating a systemic ecosystem *(Figure 28)*. Lastly, *AlgiKnit* uses science and design to rethink textile production and produce yarns from algae *(Figure 29)*.

Biodesign is a field triggering much hype in times where social and environmental issues are reshaping our economic structures. Nevertheless, as designers we must be critical in the way we approach it. My stance for a prosperous development of the practice is two-fold. First, designers alone cannot solve the wicked problems of our times; therefore, transdisciplinary collaboration must be encouraged with scalable challenges, making learning part of the process (e.g. building a common language), and focusing on solving specific problems (Cundill et al. 2018). Second, upcoming (bio)designers must be educated with a sustainability mindset. We need to design for and with the planet, while contributing to the use of systems thinking in current and future design processes (Mononen, 2017).

Figure 28. Microbial Home.

Figure 27. Biolace.

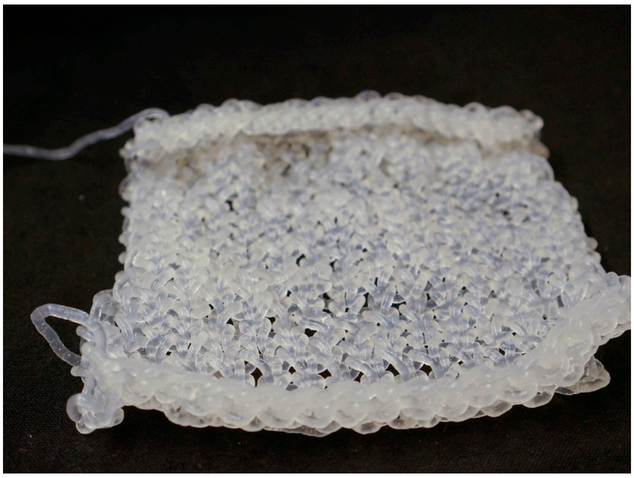


Figure 29. AlgiKnit.

4.4 AN ARTIFICIAL NATURAL FUTURE

One critical aspect often unrecognized in biodesign literature is the conceptual problem of what is *natural* and what is *artificial*. It is a complex topic, but it is crucial to recognize it – briefly- when addressing the creation of fungal leather-like materials.

In its broadest form, natural science is "knowledge about natural objects and phenomena (Simon, 1969, p.3)." Hence, the biological matter used to practice biodesign is considered *natural*, but as Bensaude-Vincent and Newman argue, the human practice of materializing (e.g. biofabrication) or modifying (e.g. synthetic biology) nature makes the end result of the practice *artificial* (2007). In this sense, the leather-like materials produced in this research are both, natural and artificial. They are natural because they promote sustainable production through biological means but are also artificial due to my own manipulation of the material.

In that respect, Nigel Cross is correct in that "what designers especially know about is the 'artificial world' – the human-made world of artifacts" (2000, p.54). However, in defense of the discipline of design and its interest to design for sustainability, I differ with Cross' reasoning when he states that "what they [designers] especially know how to do is the proposing of additions to and changes to the artificial world" (2010, p.54). More than just additions or changes, I perceive the discipline and its future development as one that also sets systemic order and evokes questions, whether *natural* or *artificial*. It is through practices like biodesign and speculative design that designers are able to understand better nature's laws and challenge utopian and dystopian images of the future as we develop an artificial natural future.

All materials come from nature, whether chemical or biological. They were extracted from the Earth at some stage. As we design a *natural* – but in theory *artificial* – future, designers should be critical and be aware of the interplay in these definitions (Simon, 1969). With every action we take, we should consider the following question: "To what extent can the materials worked on and the actions of the technician transforming the raw materials shape and reshape our concepts of nature, or of life itself?" (Bensaude-Vincent & Newman 2007, p. 9). Only then, our understanding of what is *natural* and what is *artificial* will allow us to analyze how much of our surroundings are *natural* and how much of it has become *naturally artificial*.

4.5 A NEW WAVE OF (BIO)MATERIAL DESIGNERS

The scale of human activity and projected changes in climate, economic demand, urbanization, and access to resources over the next decades require new standards of energy and water efficiency, waste elimination, and biodiversity protection. This urgency has resulted in materials transforming our design and manufacturing processes (Niinimäki et al., 2017; Ashby, 2012; Prendeville et al., 2014).

As Serena Camere and Elvin Karana explain, many of the choices made during the design phase can determine a product's environmental impact (2017). For example, in the clothing industry, designers can choose to reduce the amount of materials needed in the overall design of a product, design to increase emotional attachment to products, opt for customization or modular structures, or extend the product life cycle by planning its reuse and second-life (Niinimäki & Hassi, 2011; Ashby, 2012; Bocken et al., 2016; Bakker et al., 2014). As a result, an increasing number of alternative materials are being developed to promote sustainable design and manufacturing practices. This includes materials from renewable resources, recycled materials, revived materials (produced from discarded resources), and biofabricated materials (Vezzoli & Manzini, 2008; Sultan et al., 2017; Sauerwein et al., 2017).

The growing interest in biofabricated materials is leading to a new wave of *(bio)material designers* interested in both design and manufacturing systems that incorporate the conservation of land, water, and air (Myers, 2012). This need for sustainable and responsible use of resources has taken designers a step back in their design process. Designers no longer are selecting materials to manifest their ideas, but rather designing the materials themselves, thus, nourishing the relationship

Figure 30. Material sample *(B. robillardoides)*.

between material, process, and form (Niedderer, 2012). This is true for product and industrial designers, but also fashion and former visual designers like me who have drifted from the conventional forms of designing. Nevertheless, this material practice has a direct impact on product and industrial design as well as the manufacturing sector.

Designers are tackling biofabrication in two ways. One is by growing materials through *DIY (Do It Yourself)* practices (Camere & Karana, 2017). The second is through practical work conducted in laboratories, the latter being the central focus of this research. Our design workspaces are no longer confined to a desk, a computer, and design software, but rather petri dishes, living organisms, and beakers. This intervention in laboratories is slowly providing answers to questions from the design research community such as "Can the designer be in all cases the facilitator who enables different disciplines to work together? Is the designer's skillset and understanding enough when aiming for material innovation?" (Niinimäki et al., 2017, p. S4435).

Our role as *(bio)material designers* and intervention with other experts can have a positive impact in the life cycle assessment of a product in various ways. This includes handling the sourcing of materials (e.g. using local or waste streams), proving sustainable applications for the material (e.g. using less materials), and considering the end-of-life stage (e.g. increasing emotional attachment by designing for unique product experiences). The exact role of designers in laboratories is not yet defined, but this will change as more *(bio)material designers* get involved in enhancing design through nature (Rognoli et al., 2015, Karana et al., 2017; Chapman, 2015).

4.6 DEFINING A PATHWAY FOR BIODESIGN

As previously mentioned, the opportunity to explore biology through design – *biodesign* - is generating a new wave of *(bio) material designers*. However, through my own laboratory work, I learned how the process still lacks practical direction and theoretical grounding. As a result, I remained flexible and adapted methodologies to fit my own material-driven research. Different pathways were considered when defining my own which are covered below.

When aiming for material research and development in design, the selection of available methods is rather limited. Two popular methods for material-driven research are

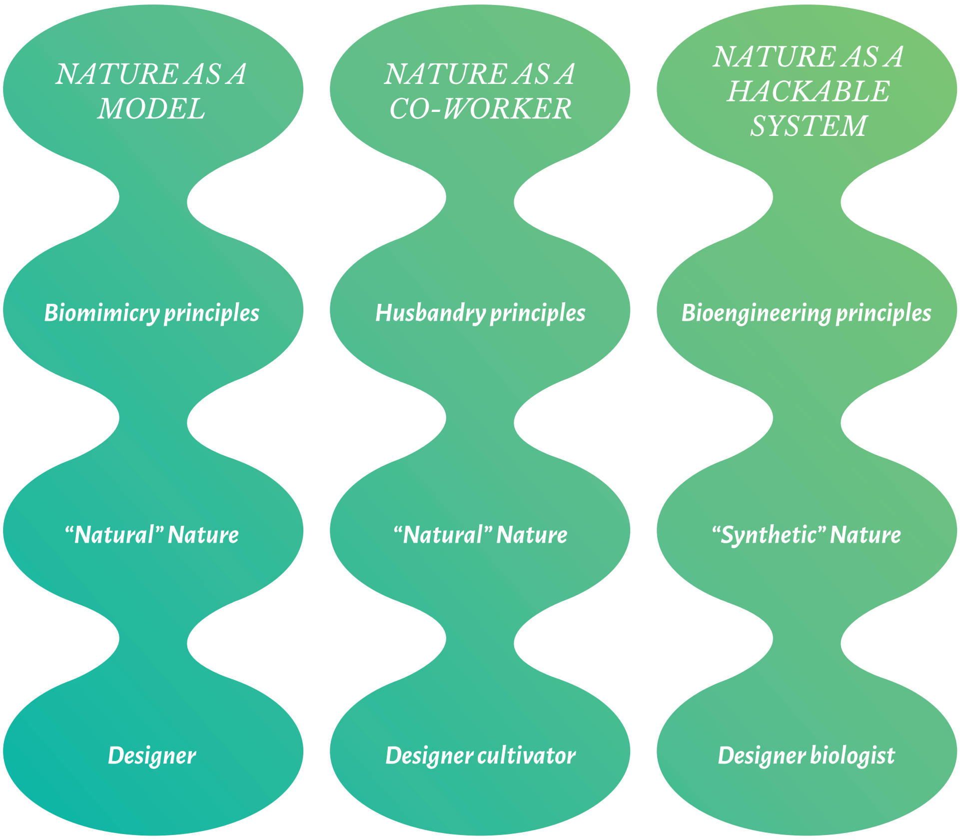


Figure 31. Model for designing with living organisms by Carole Collet. Adapted from "Grow-Made Textiles," by C. Collet, 2017, In Karana, E., Giaccardi, E., Nimkulrat, N., Niedderer, & K., Camere, S. (Eds.), *Alive Active Adaptive: Proceedings of EKSIG2017, International Conference on Experiential Knowledge and Emerging Materials* (pp. 26). Delft, The Netherlands: TU Delft Open. Copyright 2017 by Collet, C., Karana, E., Giaccardi, E., Nimkulrat, N., Niedderer, K., & Camere, S. Adapted with permission.

the Design Driven Material Innovation (DDMI) method by the Material Design Culture Research Centre (MADEC) of Politecnico di Milano (Lecce, C., & Ferrara, 2016) and the Material Driven Design (MDD) method by a group of researchers from Delft University led by Karana (Karana et al., 2015). They both make material-driven research possible but have some drawbacks when utilized for research in laboratories with materials not fully developed. The DDMI method is too market-oriented and not very effective in circumstances where the material properties are not well defined and exploratory samples are used. On the other hand, the MDD method is mostly centered on *DIY* practices and possesses little understanding of laboratory environments for biofabrication. In fact, there is currently no concrete method for designing specifically with living organisms. Nevertheless, as discussed in *Chapter 3*, the MDD method was the one closest to the research and provided methodological flexibility for an effective application in this work.

Even though research for materials not fully developed in laboratory environments still require better methodologies, Carole Collet from Central Saint Martins, proposes a framework for designing with living organisms *(Figure 31)*. Collet identifies a set of principles for collaborating with the living and help to reposition the role of the designer in techno-scientific environments (2017).

The first category, *nature as a model*, sees designers as *plagiarists*. It embraces biomimicry by looking at nature as it is *(natural nature)* for inspiration. Here, the designer's role remains as is, a *designer.* While a good sustainable alternative, it is important to note that not all biomimicry is sustainable since the manufacturing might require traditional production and sourcing (Collet, 2017). Also, as Myers states, biomimicry is not biodesign (2012). Biomimicry seeks nature for inspiration and emulation of natural systems (e.g. creating materials with hydrophobic capacities resembling fungi), while the latter incorporates the natural systems within the design (e.g. fabricating materials using the growing properties of fungi). This differentiation is crucial (Myers, 2012).

The second category, *nature as a co-worker*, portrays designers as *cultivators*. It incorporates the use of living organisms as part of the design or production process. As described in the previous category, nature remains as is *(natural nature)* and husbandry principles are applied. The designer becomes an active collaborator with the living organism by relying on nature's ways for production (Collet, 2017). While the author does not mention biofabrication as such within this model, it fits best here.

The third category, nature as a hackable system, depicts designers as *biologists*. It works in a more radical manner as it aims to alter biological systems through engineering. Therefore, based on the author's views, nature is no longer *natural*, but rather *synthetic*. Bioengineering principles are at the core of design production (Collet, 2017).

Lastly, from the model it is concluded that *nature as a co-worker* and *nature as a hackable system* fit under the principles of biodesign practices, but not *nature as a model* (Myers, 2012; Collet, 2017).

Referring back to *nature as a co-worker*, Collet denotes important observations which are central to this work (2017). In biodesign, collaboration is perceived mostly between the designer and the other disciplines. However, a fundamental collaboration exists between the designer and living organism. If in husbandry, practitioners act as care takers for the cultivation of crops, then a similar aspect happens when working with organisms like fungi, bacteria, or algae. Designers immerse in an intimate interaction as they grow and incorporate the properties of the living matter within the production of products or materials (Collet, 2017). Understanding the collaboration from the perspectives of the disciplines and the living organisms were essential in this research. This experience is narrated in the following section.

Figure 32. Material sample before taking it out to dry *(B. robillardoides)*.

5: THE PROCESS OF BIOFABRICATING WITH MYCELIUM

5: THE PROCESS OF BIOFABRICATING WITH MYCELIUM

This chapter covers all the practical work. The process of biofabricating leather-like materials from fungi is situated under the practice of biodesign following some of the principles of speculative design. This practice brought me to examine the collaboration with both experts and living organisms. Fungi served as the central point to integrate practice and knowledge among disciplines as well as to study the material's properties and growing behavior. In this chapter, I provide a more personal approach to narrate my experience.

First, I introduce *The Laboratory as a Space for Transdisciplinary Collaboration* where I discuss my experience with the experts I collaborated with. Second, I expose my interaction with the material in *The Laboratory as a Space for Material Exploration*. Third, I define the topic of mycelium to ease the understanding of the sections that follow and describe all technical procedures required when working with mycelium.

The chapter proceeds with three more sections to depict my design process applying the adapted version of the Material Driven Design (MDD) method. In *Material Exploration: Understanding the Material in the Laboratory,* I describe the different experiments conducted where plenty of material-tinkering was applied. I close the section by delivering an evaluation of the main insights obtained in the experiments. In *Material Analysis: Creating Material Experiences and Future Visions with Users,* I introduce the topic of *materials experience* as part of the MDD method. Then, I provide the evaluation of results obtained in the workshops and interviews where the material samples from the previous section were utilized. In the last section, *Material Prototypes: Unfolding Alternate Material Futures,* I present three speculative case studies depicting the material experiences and future applications for the selected fungal leather-like materials by the participants in the workshops and interviews.

5.1 THE LABORATORY AS A SPACE FOR TRANSDISCIPLINARY COLLABORATION

The laboratory provided a physical space to collaborate with experts and integrate disciplinary practice and knowledge (Niinimäki, Groth, & Kääriäinen, 2018). Living matter – *biodesign* - and future visions - *speculative design* - intertwined to understand better the future collaboration between designers and scientists when working towards material-driven research.

There are several ways to classify the collaboration between disciplines (e.g. interdisciplinary, multidisciplinary). However, it is not yet possible to define exactly what constitutes each one of them. Based on Muratovski's views, I perceived my collaboration with experts at VTT Technical Research Centre of Finland as transdisciplinary (2015). It required me to transcend from my own traditional design norms and adopt new ways of working from the discipline of biology. In the laboratory, as Matt Malpass states, "the process of doing science itself… figured as the design process" (2017, pg. 105). While there are still research gaps in transdisciplinary literature, less is known about how designers undertake work in places destined to other disciplines such as laboratories. My process began with biology knowledge dating back to high school and my understanding of leather-like materials from fungi originated from articles I read online. Little did I know that concerning grown materials, what one reads and sees online, it is not easy to obtain in practice. With this challenge ahead I turned to design thinking to guide my initial process.

As Herbert Simon claims, design is about "changing existing situations into preferred ones" (1969, p.111). Thereby, design is, for the most part, concerned with how things work or should work, while science is concerned with how things are. In this respect, my collaboration at VTT started by grasping as much as I could from biology to build a common language with the scientific environment that would fit my own disciplinary conditions and those of whom I worked with (mostly material scientists and material engineers). In the beginning, it was essential to be curious, adaptable, and open-minded. It allowed me to build a clearer picture of ways to undertake the development of fungal leather-like materials with experts from biology and related fields.

As the research proceeded forward, biology and design principles began to merge. As Kirsi Niinimäki explains, "tangible, tacit and theoretical knowledge can be linked together to form understanding of the situation at hand" (2018, p. 3). However, the linking of this common understanding was faced with some barriers. Some of these barriers were: different organizational skills for conducting experiments; the need to comprehend that design embraces uncertainty and likes to go against the rules in design; different disciplinary languages; and the most challenging one - brains used to solving problems in different ways. Designers are used to tackling problems in various settings and in a more experimental way using imagination as a tool, while scientists are used to solving problems in controlled laboratory environments using qualitative and quantitative methods (Niinimäki et al., 2017). As the collaboration progressed, we formed patches of interpretations and explanations from both disciplines. Sharing insights, best practices, and methods was challenging at first, but as those barriers were overcome, the process became more organic and a cross-fertilization of design and biology took place (Grix, 2010).

The joint practices in the laboratory (also those during the workshops) allowed everyone to build a shared mindset, vocabulary, and understanding of what was feasible within the scope of research (Stompff & Smulers, 2013). For example, we learned what material properties meant for each one of us (e.g. designers, material scientists, material engineers). Additionally, I found intriguing how designers were mostly driven by the sensorial qualities, while scientists were more interested in their molecular structure and technical properties. However, we faced some knowledge gaps (Niinimäki et al., 2017). In some cases, the information we knew was not enough and required us to reach out to specific specialists. Some of the gaps encountered included needing a deeper knowledge about certain fungal species (e.g. mycologist), knowledge about coatings and plasticizers (e.g. material chemist), technical knowledge about spinning fibers (e.g. textile engineer), and in several occasions we required knowledge about specific equipment (e.g. specialized technicians).

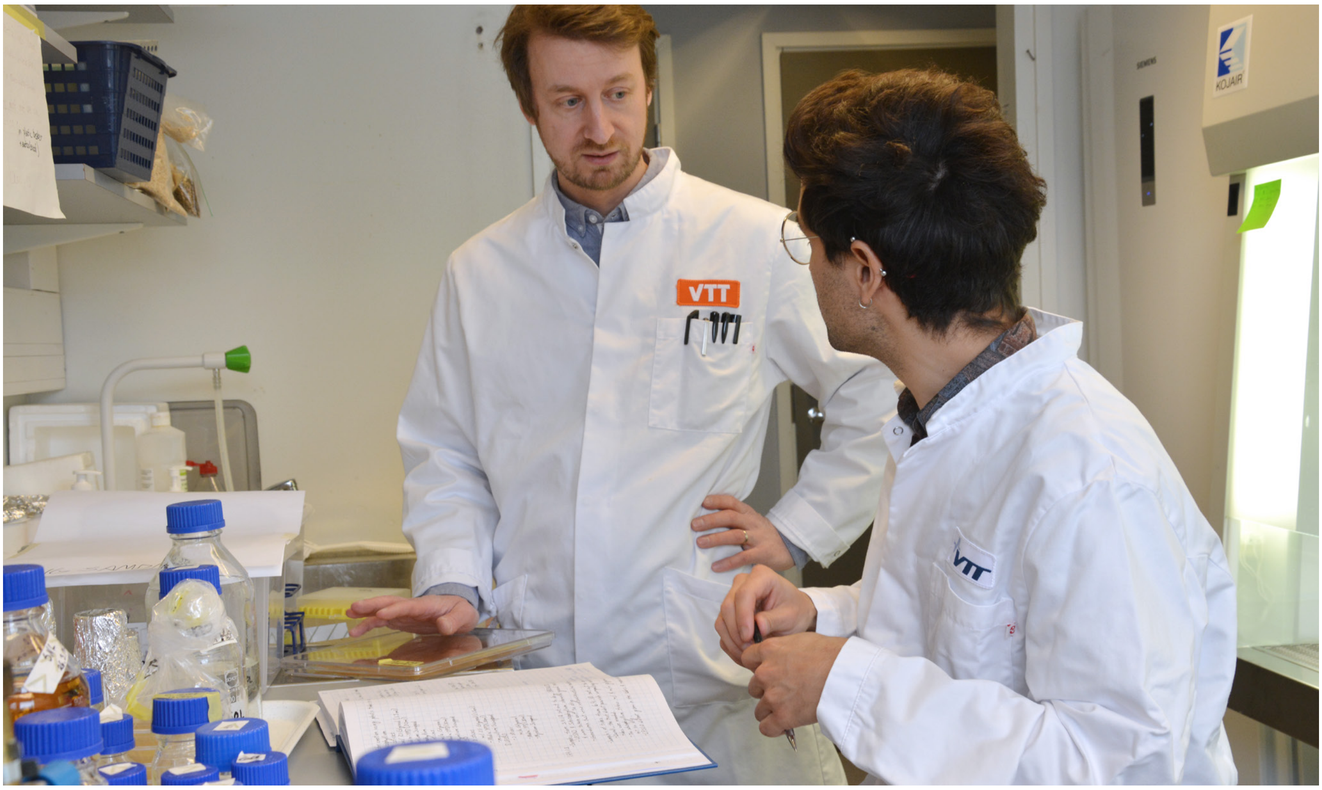


Figure 33. Discussing results.

Figure 34. Checking the growing process of *P. chrysosporium*.

In terms of my role in the laboratory, this was challenging to identify. I knew I was not a scientist, but neither a traditional designer. I remained true to my disciplinary background and took roles as an interpreter, coordinator, facilitator, and crafter. Nevertheless, there were times in the laboratory when I felt an *outsider*, especially between those who were not in my research group. For some, my design approaches seemed something abstract, but so did the science they practiced beyond my conceived knowledge of biofabrication.

Regardless of how I felt, my open-ended ways of working found their space in the laboratory. Over time, my design process entangled with the more rigid and result-oriented processes of science. A notebook with messy sketches and thoughts became a symbol of creative freedom in the laboratory in contrast to the laboratory notebook ruled with dates in chronological order, measurements, hypotheses, and results. The use of a lab coat became familiar and so did the processes of growing the leather-like materials. I introduced design terminology to the team, and I adapted to theirs. Culture, media, species, strain, and so on became part of my daily vocabulary. Design software was put aside, and the biological machinery of fungi became my playground for creating knowledge. The unique experience to collaborate with experts at VTT and integrate both practice and knowledge, called for a new skillset to enable biofabrication at the intersection of design and biology.

Figure 35. Learning a new drying method for *P. chrysosporium*.

Figure 36. Analyzing samples with the team.

5.2 THE LABORATORY AS A SPACE FOR MATERIAL EXPLORATION

In the laboratory, the biological behavior of fungi was studied through a series of experiments. The work consisted of a human-material interaction where my own practice drove me to comprehend it as a live agency, rather than imposing direct uses for the material as commonly practiced in design (Bennett, 2010 & Malafouris, 2008). This approach to collaboration resulted in unique experiences and intriguing questions that allowed me to reflect before proceeding further with new experiments (Groth & Mäkelä, 2016).

My collaboration with fungi follows the principles behind *New Materialism*, which states that all materials, biological or non-biological, are an agency of their own (Bolt 2007; Malafouris, 2008). In the laboratory, materials were accepted as entities capable of acting on their own, without the intervention of other living forces, such as my own. Allowing myself to reflect on my interaction by observing the relationship, dependency, and responsibilities (Niinimäki et al., 2018) developed over time. My explorative tactics resulted in a sense-making process (Harrison, 2000) where my actions led to new knowledge about fungi growing capacities and material possibilities.

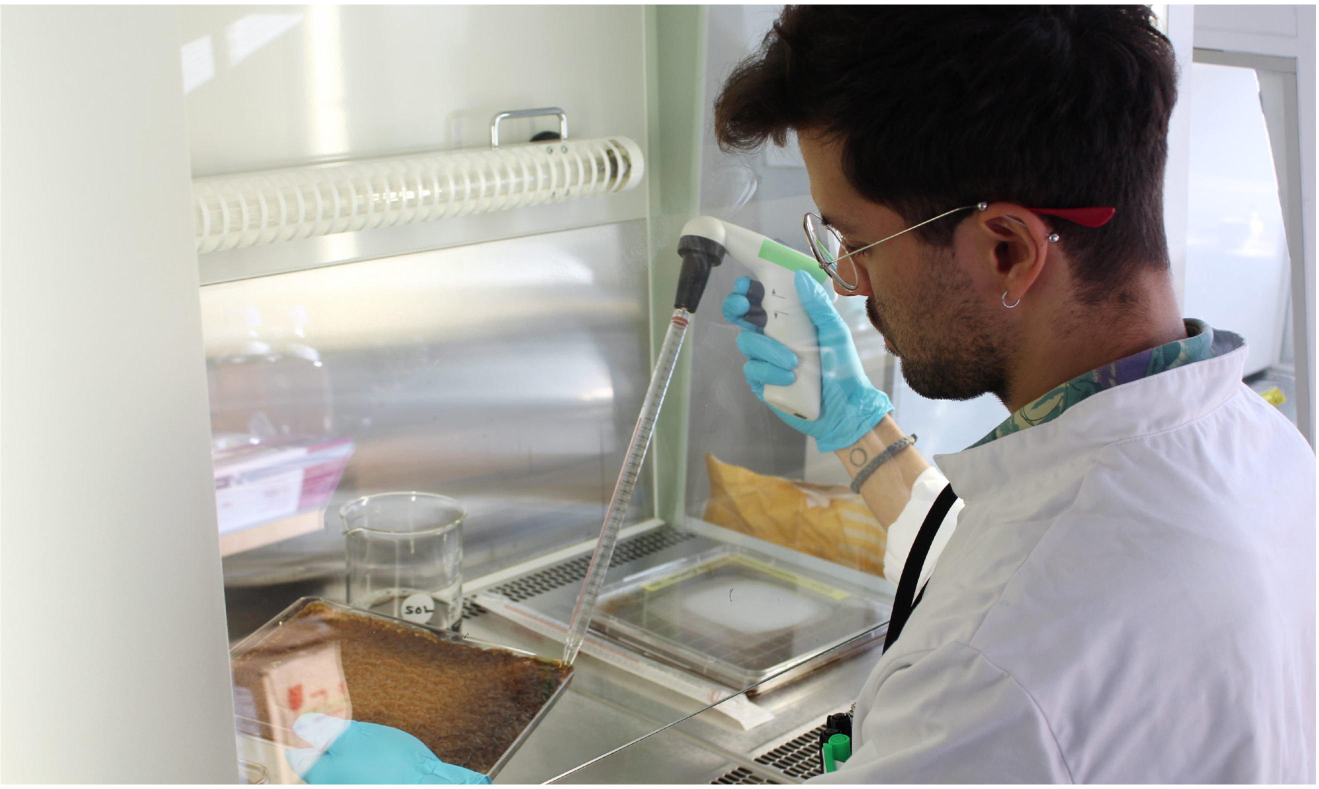


Figure 37. Getting the media out from the sample before drying it.

Figure 38. Molded material sample *(B. robillardoides)*.

My relationship with fungi began with the experiments. They acted as the medium to test hypotheses and achieve material samples. This relationship grew stronger as I continued using petri dishes, catching up with scientific language, and learning culturing techniques. I emerged into a realm of speculation with the material and its living properties. As Manzini recommends (1986), I stayed away from asking myself *what is it?* and instead asked *what does it do?* when handling different species. This triggered new ways to interact with it and resulted in a wider range of material samples depending on the type of *recipe* used (Camere & Karana, 2018). The material sometimes behaved in unpredictable ways. Depending on the day, I would be excited, upset, anxious, hopeful and even angry; I never knew what to expect. As Chen and Crilly state, living organisms like fungi are everything but linear (2016). Nevertheless, the material made tangible my desire to understand how leather-like materials could be developed and served to experience the work of future designers in laboratories.

The growing process generated a certain dependency. The more experiments I conducted, the more we were engaged to learn from each other. Camere and Karana explain this experience rather nicely by depicting the process as "co-performed with nature, concurrent, intimate, bottom-up, structured and intuitive" (2018, pp. 576-577). The co-performance, or co-work as Carole Collet calls it (2017), was enhanced every

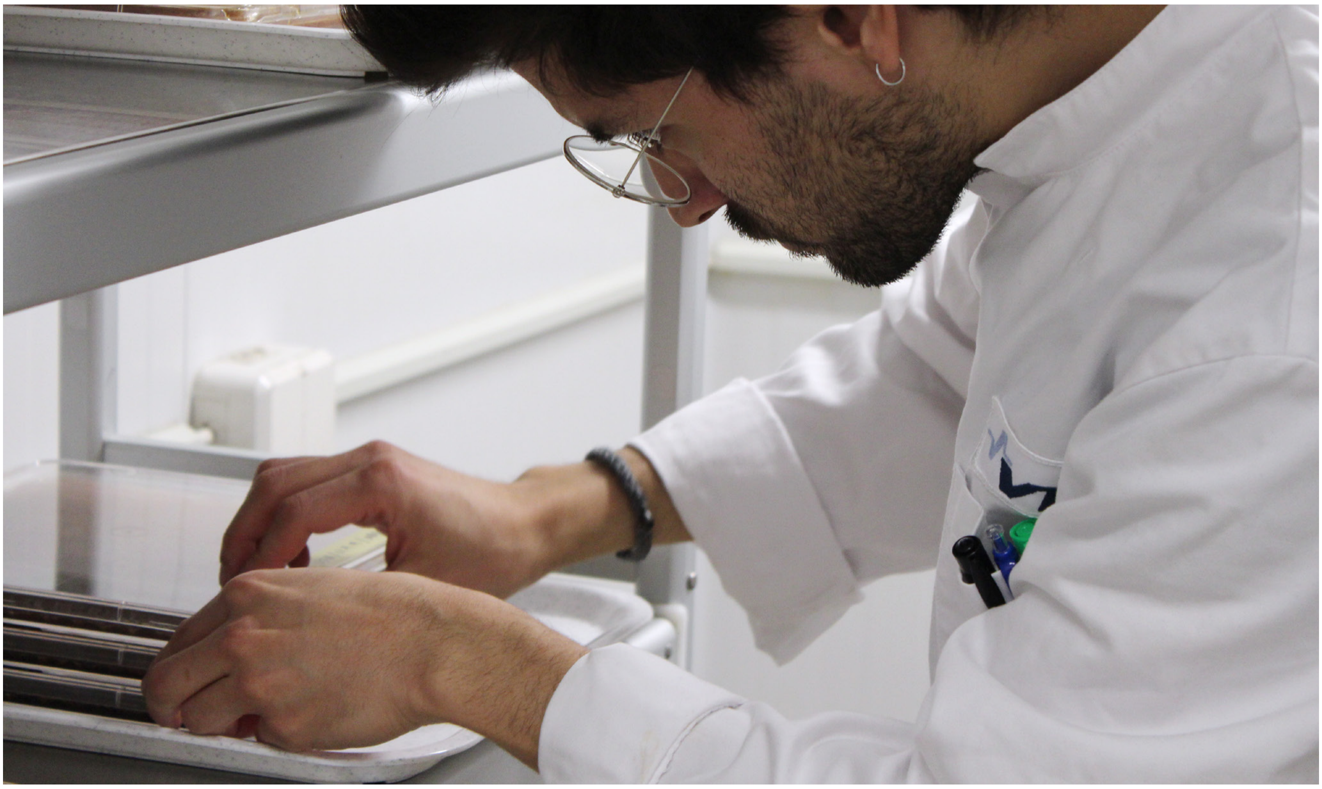


Figure 39. Putting new samples to grow in the 28° room.

time through our mutual interaction. However, I never felt I was making the material, but rather adapting it or guiding the growth. The credit of the making belongs to the living organism. The growing periods provided critical information about the organism's growing behavior. It became a very intimate process, something similar as having a pet or plants at home. Every day I checked on the growth and attended the needs of fungi when required. As Camere and Karana reveal from a comment in an interview "you have some feelings, you have something, actually, activating, into you in terms of engagement" (2018, p. 576).

Additionally, by taking the material to the very beginning of the design process, I learned how the growing patterns of living organisms should dictate the form and potential uses. I relied on different tools and techniques to yield this bottom-up approach. Over time, the laboratory became a space for both, creative freedom and structure. I was free to manage and propose diverse ways to grow the organism but was governed by strict scientific protocols. However, sometimes I felt an urge to go against the rules and was encouraged by my intuition to explore the unknown. Getting out of my comfort zone meant mixing different species of fungi, trying different waste streams as substrates, and performing things a scientist would not normally do in the laboratory such as using paint brushes, rolling pins, and inclusively an iron. They all provided solutions when the laboratory equipment did not fit my creative needs.

All in all, my interaction with fungi required a lot of responsibility. The organism was alive, it could grow anywhere and do also undesirable things in places where it was not supposed to. I learned that working with biology meant adopting traditional laboratory techniques and crafting my own design methods to feed, understand, and co-work with fungi. I learned to treat these new ways of doing design like you would human-centered processes, with the difference that there was no human, but instead a living organism situated at the core of the process with an agency of their own.

Figure 40. Laboratory tools & materials.

5.3 BIOFABRICATING WITH MYCELIUM

The use of living organisms in biofabrication offers compelling advantages to the design community, including sustainable production systems, commercial appreciation and awareness, and a reinterpretation of nature (Camere & Karana, 2018). It also presents an opportunity for designers to speculate the future role of living organisms in the manufacturing of products. The material practice of *growing* derives from the following biological organisms: fungi (mycelium), bacteria, and algae. In this research, fungi are at the core of the material exploration, explained in detail here.

Mycelium is defined as a network of interconnected filaments called hyphae that comprise the vegetative part of mushrooms (Kavanagh, 2011). Put in simple terms, the process begins with the release of a *spore* which then grows into a filament called a *hypha*, and consequently, extends and branches into a network of hyphae called *mycelium*. *Figure 41* illustrates this process. It is important to note that we did not work with mushrooms, but rather mycelium which resides in the soil to feed mushrooms. However, we can call it fungi, as they all belong to the kingdom of fungi (Kavanagh, 2011). Throughout history, these organisms have been studied for food production (e.g. cheese) and medical purposes (e.g. antibiotics). Interestingly, it is not until recently that mycelium has begun to be studied as a resource for bio-based material making (Holt et al., 2012; Jiang et al., 2013).

There are two alternative methods to produce mycelium-based materials. The first one is by activating mycelium to bind with other substrates (e.g. organic substrates) to create a bulk material, identified in this research as *mycelium-based composites* (Holt et al., 2012). The second method of production is achieved by exploiting a liquid culture of mycelium, defined in this work as *pure mycelium* (Haneef et al., 2017; Montalti, 2013). *Figure 42* shows the difference between them.

This material practice began with designers exploring mycelium-based composites since the process of fabrication is relatively more stable and accessible than that of pure mycelium. However, recent interest in other properties of the material has pushed designers and companies to explore pure mycelium as well. In this research, both methods were explored, allowing better understanding of fungi's agency. Nevertheless, most of the samples were obtained from liquid cultures using pure mycelium.

The process to grow mycelium-based composites start by inoculating a *strain* of fungi in a substrate of organic substances (Holt et al., 2012). A network of mycelium grows by using the organic substance (e.g. coffee grounds) as food and colonizing it. The end result is a bulk material covered by a white, soft skin (Jones et al., 2017). *Figure 43* illustrates this result. The substrate must assist mycelium with the necessary nutrients for its growth. This includes carbon (e.g., glucose or fructose), nitrogen, minerals, and vitamins, in addition to water. The right percentage of water when preparing the substrate is crucial (Carlile et al., 1994; Deacon, 1980; Jones et al., 2017). The substrate can come from various sources including waste

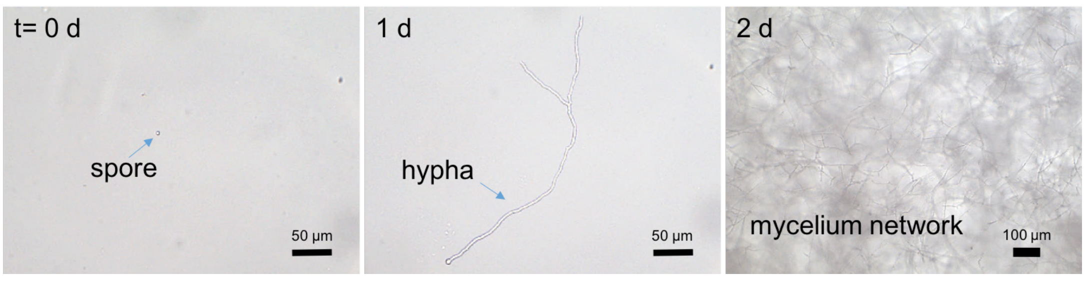


Figure 41. Growing process of mycelium.

Figure 42. Mycelium-based composite (left) and pure mycelium (right).

streams from agriculture like wheat or rice straw, wood such as sawdust, or cellulosic fibers like cotton (Kavanagh, 2011; Jiang et al., 2013; Lelivelt et al., 2015). However, in terms of fibers, we also experimented in this research with synthetic fibers like polyester and protein-based fibers like wool.

The process to grow pure mycelium in liquid cultures follows a similar approach, but the culturing of the spores can happen in two forms, either standing (static) or shaken (machine-shaken unit). If grown as a standing culture, a sheet grows on top of the liquid. Once dried, the material properties appear similar to those of animal leather, paper, or plastic (Karana et al., 2018). If grown as a shaken culture, depending on the strain, the end result might be a viscous or slimy substance. *Figure 44* illustrates these two types of results. The media used to grow the spores in liquid cultures can vary, but as in the same case with mycelium-based composites, it must assist mycelium with the necessary nutrients for its growth. In both growing processes, the media or any other additives given to the mycelium before or after growing, can affect the color,

Figure 43. Mycelium grown as a mycelium-based composite with coffee grounds.

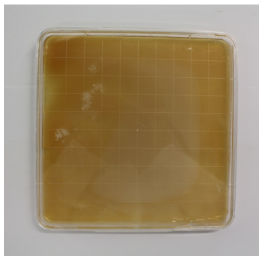


Figure 44. Difference between mycelium grown as a standing liquid culture (top) and shaken liquid culture (bottom).

translucency and stiffness (Karana et al., 2018). The process to grow either mycelium-based composites or pure mycelium is shown *Figure 45*.

In the process of fabrication with fungi, a high level of sterility is crucial to obtain appropriate results and avoid contamination (Jiang et al., 2013). Including, but not limited to, the substrates used for mycelium to grow as well as the workspace and tools used when handling the organisms. Furthermore, the setting for culturing mycelium must maintain controlled environmental conditions of light, temperature, and moisture to guarantee a steady growth in a period of two to three weeks (Carlile et al., 1994). The conditions for temperature and moisture can change significantly depending on the strain of fungi used, but 24-35° is recommended (Jones et al.; 2017). Since water is an important nutrient for the metabolism of fungi, the humidity should be kept at 60-65% to prevent the drying of the substrate (Carlile et al., 1994). Once the growing process finishes based on expected and desired needs, the mycelial samples can be killed by drying it at a minimum of 60°C (Kavanagh, 2011), or kept in hibernation by keeping it in its natural state for other purposes (Karana et al., 2018).

Some of the unique properties of the material is that it offers designers the opportunity to grow it into specific shapes using molds. Additionally, different processing techniques can be applied onto the material such as laser cutting and cold or hot compression to obtain the desired results (Jiang et al., 2016). Depending on the strain, hydrophobicity is also a feature that can be incorporated as part of the design. Furthermore, if the material is kept alive, it can also function as a self-healing unit of its own. Lastly, it can be used as printing material for 3D printers and sewing is also possible depending on the material's strength. Overall, the material properties can vary extensively depending on the applied techniques (Yang et al., 2017).

While there are many people and companies getting involved in this practice, there are currently just a few leading the research and development of mycelium-based materials. These include Ecovative, MycoWorks, and Bolt Threads. Ecovative was founded in 2007 by Eben Bayer and Gavin McIntyre. Their initial products included a mycelium-based packaging material called MycoComposite™ and the company recently extended to the development of an alternative to foam called MycoFlex™. Elsewhere, Philip Ross along with Sofia Wang and Eddie Pavlu, founded MycoWorks in 2009 and launched a leather-like material grown from mycelium. Recently, Bolt Threads became a leading company in the field of mycelium leather with their material brand Mylo™, done in collaboration with Ecovative. Other players in the field include Eric Klarenbeek, Aniela Hoitink, and Maurizio Montalti. Klarenbeek is known for his furniture work with mycelium where he incorporated technologies like 3D printing. Hoitink, instead uses mycelium to create textiles; white still at research stages and not yet commercialized, her material approach is promising. Situated between functionality and art is Montalti from Officina Corpuscoli who uses mycelium as a medium to envision and design products. *Figure 46* shows a collection of

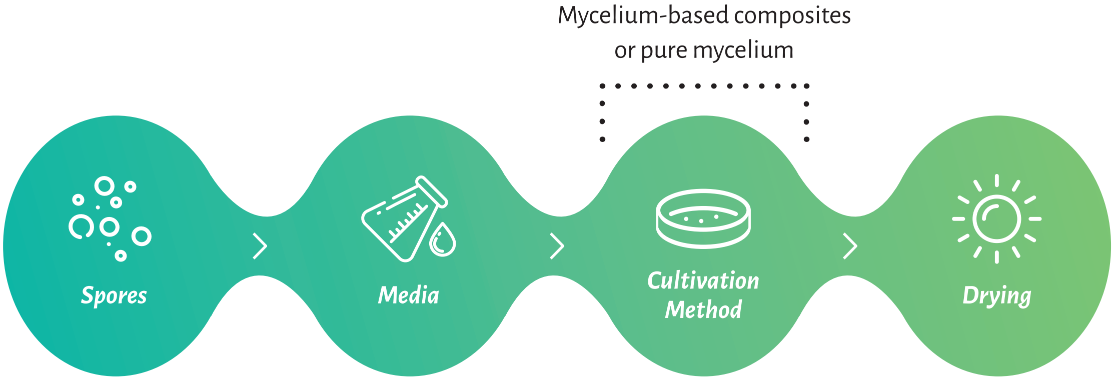


Figure 45. Process to grow either mycelium-based composites or pure mycelium.

works from the mentioned people and companies.

As environmental pressures increase, so will the number of individuals interested in the practice of biofabrication using mycelium. It has many advantages as it does not require the extraction of raw materials from the Earth's crust, uses limited amounts of energy, does not use any toxins, and since it is biodegradable its disposal can nurture the growth of new materials (Jones et al., 2017; Jiang et al., 2013; Holt et al., 2012).

As proposed in *Chapter 3*, my approach to mycelium-based materials is based on the adaptation of the MDD method, which is discussed next by looking separately at each of the three parts that it is composed of.

Mylo™ by Bolt Threads

MycoFlex™ by Ecovative

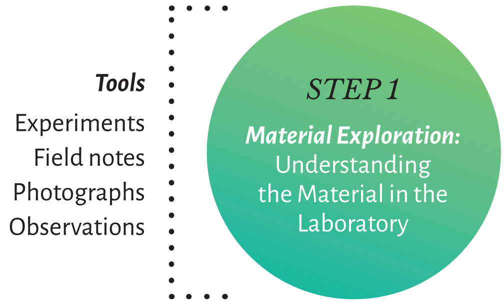
MycoWorks

Maurizio Montalti

Aniela Hoitink

Eric Klarenbeek

Figure 46. Examples of mycelium-based materials and products.



5.4 MATERIAL EXPLORATION: UNDERSTANDING THE MATERIAL IN THE LABORATORY

The step of material exploration represents my engagement with fungi to create leather-like material samples. The collaboration with several experts provided a holistic view to integrate our disciplinary practice and knowledge and set forth my interaction with the material. The material-driven process consisted of hands-on experimentation using *material tinkering* (Parisi & Rognoli, 2017). The tools used in this step include the experiments, field notes, photographs, and observations.

My process started by taking as reference any previous knowledge with materials to guide my actions and using animal leather as material inspiration or point of comparison. The sharing of information between the experts and I was essential in this phase. In the laboratory, I was clear that our goal was to create leather-like materials from fungi, but this topic was new for everyone in the laboratory. Nonetheless, I started the exploration by selecting different species of fungi, testing different media on them, and thinking about different substrates that could be used.

It was challenging to set a path for the material exploration. As I conducted the first experiments, most of my speculations were related to mechanical properties (e.g. How can we make it flexible?) and growing behavior (e.g. How long will it take to grow?). As Groth and Mäkelä recognize, it was clear that my previous experiences and knowledge with other material properties provided the basis for new material experiences when diving into the unknown (2016). Upon obtaining the first few material samples, an experiential awareness for material qualities arose. The more experiments I conducted, the more intimate the interaction, and the more ways I learned to co-work with mycelium. The hands-on approach to experimentation using material tinkering contributed greatly to my interaction with the living agency of fungi. It helped me to obtain data, comprehend material properties, understand constraints, and identify all potential opportunities for it (Parisi & Rognoli, 2017). The creative freedom of tinkering invited me to play by cutting, ripping, burning, and even sewing the material.

Figure 47. Step 1 of the Material Driven Design (MDD) method in the context of this research. Adapted from "Material Driven Design (MDD): A Method to Design for Material Experiences," by E. Karana, B. Barati, V. Rognoli, & A. Zeeuw van der Laan, 2015, *International Journal of Design*, 9(2), 35-54 (p. 40). Copyright 2015 by International Journal of Design. Adapted with permission.

In addition to the experiments, the process of tinkering also involved field notes, photographs, and observations. They served as tools to document my successes and failures. Sometimes, what I first thought was a good idea, in practice was not. The entire process was trial and error. However, all exploration contributed to building a holistic understanding of the material. The bond built between me and fungi made it possible to master the growing behavior of some species more than others. The more I knew the behavior of a species, the more I was able to think outside the box (Parisi et al. 2017).

The experiments were conducted by me during a period of ten months approximately, but of course, always in close collaboration with scientists at VTT. They provided daily guidance to my work at the laboratory. We started the research with the species of Trichoderma reesei (strain used: M48), Phanerochaete chrysosporium (VTT-D-84237), Fusarium fujikuroi (M2039 and M2040), Fusarium oxysporum (M2043), and Bartalinea robillardoides (LF550, VTT-D-121440). All used *Fusarium* strains were kind gifts from prof. Carmen Limón, University of Seville, Spain, and the strain LF550 kindly provided by prof. Johannes Imhoff, Kieler Wirkstoff Zentrum-IMF Geomar, Kiel, Germany. As the exploration progressed, the species Schizophyllum commune (VTT-D-88362), Ganoderma lucidum (VTT-D-06390), Fomes fomentarius (VTT-D-061139) and Pleurotus ostreatus (VTT-D-90415) were brought into the experimentation. We also used the bacteria Gluconacetobacter xylinus (VTT-E-92004) for some experiments at later stages of the research. Depending on the type of species, the substrates used to grow the material were yeast potato extract (YPD), trichoderma minimal medium (TrMM), potato dextrose (PD), or malt extract (MEA). I experimented with all eight species throughout the material exploration in an achronological manner. They were led by hypotheses that would be framed (or reframed) as new samples and insights were obtained.

As mentioned in the previous section, the experimentation involved both mycelium-based composites grown using organic substances, and pure mycelium grown as liquid cultures (standing and shaken). Most materials were grown during a period of four days to two weeks approximately with adequate light and moisture, at 28°C. In some occasions, drying was employed using heat temperatures below 100°C to deactivate the living organism. The nutrients and *recipes* to grow fungi varied depending on the material properties and experiential qualities sought after. To ease understanding, the following names are applied when referring to the containers used: Petri dish - standard size - (90mm × 15mm), big petri dish (14mm × 20mm), small petri dish (53mm × 13mm), extra small petri dish (38mm × 12mm), squared petri dish (245mm x 245mm x 25mm). The details of each of the experiments are included in the next section called *Material Motivations.*

5.4.1 Material Motivations

As stated by Bang et al. (2012) in their Constructive Design Research model, motivations are fundamental. They enhance the process of hypothesis-making, create interdependence among the other steps, and advance the creation of knowledge through each experiment *(Figure 48)*. These motivations can come from various sources. In the case of my research, they came from previous experiences with the mechanical properties and experiential qualities of materials.

The material motivations are my explorative approach to build collaborative knowledge and foster my interaction with the material. To emphasize the motivational context behind each experiment, they are classified as: *flexibility*, *growth*, *growth in waste*, *mixed growth*, *strength*, *color*, *coating*, and *scaling up*.

Each experiment includes a hypothesis, the sample preparation, and the results. The final evaluation of the experiments is disclosed in the next section. The experiments below are presented based on the classification of material motivations, not necessarily in the order they were conducted.

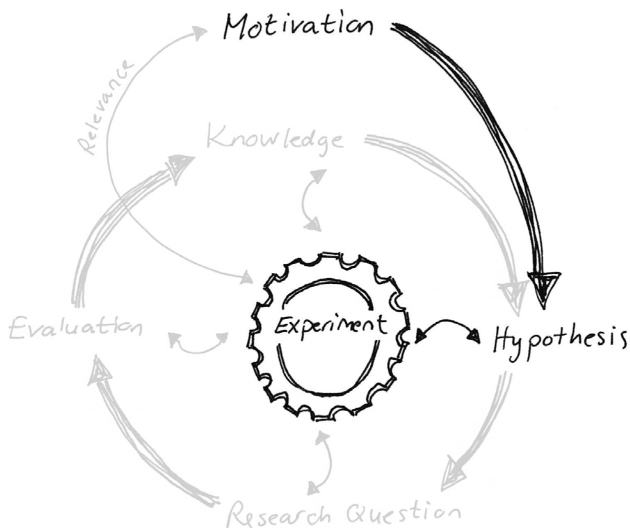


Figure 48. Segment of the Constructive Design Research model. Adapted from "The Role of Hypothesis in Constructive Design Research," by A. L. Bang, P. G. Krogh, M. Ludvigsen, & T. Markussen, 2012, *Kolding School of Design*, p. 6. Copyright 2012 by Kolding School of Design. Adapted with permission.

5.4.1.1 Flexibility

Flexibility was one of my main concerns through the entire exploration. My preconceived knowledge of animal leather took me to inherently make this material property a priority in the research. This material motivation began by wondering what type of natural substances could make the material flexible without compromising its growth. In the end, flexibility was mostly achieved by the use of glycerol and oil using different percentages. There were tested separately and altogether depending on the experiment.

Hypothesis: Glycerol can act a plasticizer to make *P. chrysosporium* more flexible.

Sample preparation: Four squared petri dishes were used in this experiment. $8 \cdot 10^6$ of spores from *P. chrysosporium* were grown in 200 ml of YPD. The culture media was supplemented with 0% (control), 1, 2%, and 4% glycerol. After five days, the samples were stopped and air dried.

Result: The sample containing 2% glycerol showed the best results in terms of flexibility. Below 2%, the samples broke easily and above it, they were too sticky.

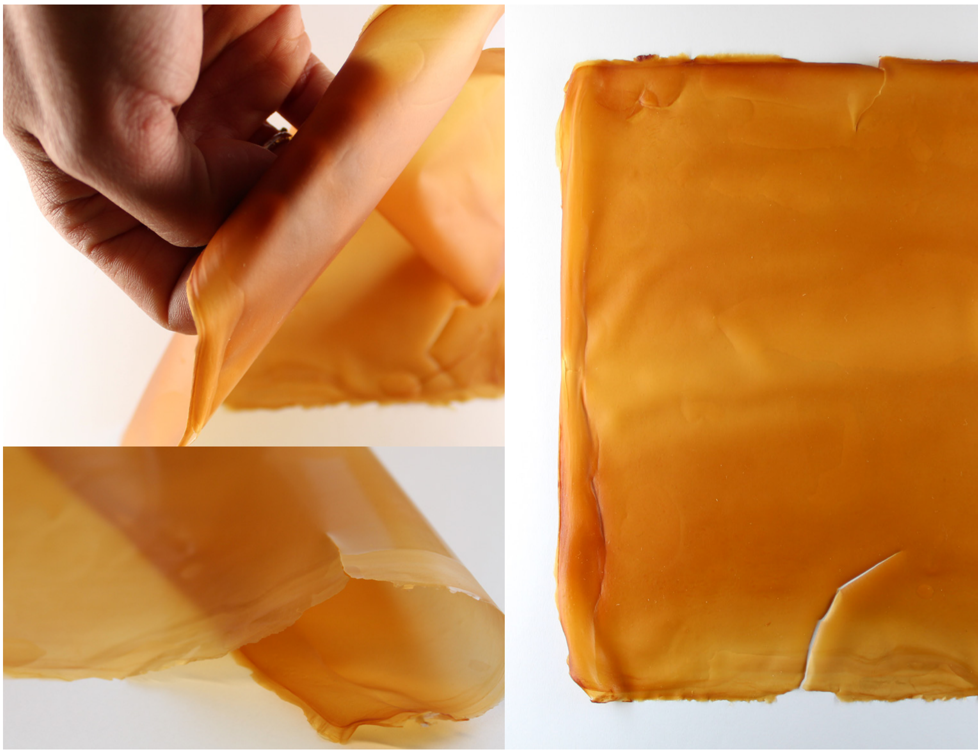


Figure 49. Flexibility 1.

Figure 50. Flexibility 2.

Hypothesis: Vegetable oil can act as a plasticizer to make *P. chrysosporium* more flexible.

Sample preparation: Three squared petri dishes were used in this experiment. $8 \cdot 10^6$ of spores from *P. chrysosporium* were grown in 200 ml of YPD and 2% glycerol. The control contained only 2% glycerol and no oil, while the other two contained 2.5% oil and 5% oil. After five days, the samples were stopped and air dried.

Result: The sample containing 5% oil gave the best results in terms of flexibility.

Hypothesis: Glycerol can act as a plasticizer to make *B. robillardoides* more flexible.

Sample preparation: Four squared petri dishes were used in this experiment. Scraped spores from *B. robillardoides* were grown in 200 ml of YPD. Depending on the desired percentage of glycerol, the following were added in each of the squared petri dishes: 0% (control), 1, 2%, and 4%. After seven days, the samples were stopped and air dried.

Result: The sample containing 2% of glycerol showed the best results in terms of flexibility. Below 2%, the samples would break easily and above it, they were too sticky.

Figure 51. Flexibility 3.

Hypothesis: Vegetable oil can act as a plasticizer to make *B. robillardoides* more flexible.

Sample preparation: Three squared petri dishes were used in this experiment. Scraped spores from *B. robillardoides* were grown in 200 ml of YPD and 2% glycerol. The control contained only 2% glycerol and no oil, while the other two contained 2.5% oil and 5% oil. After seven days, the samples were stopped and air dried.

Result: The sample containing 5% oil gave the best results in terms of flexibility. Additionally, it was found that by adding oil, the texture and pattern of the material changed compared to the sample of *B. robillardoides* containing only 2% glycerol.

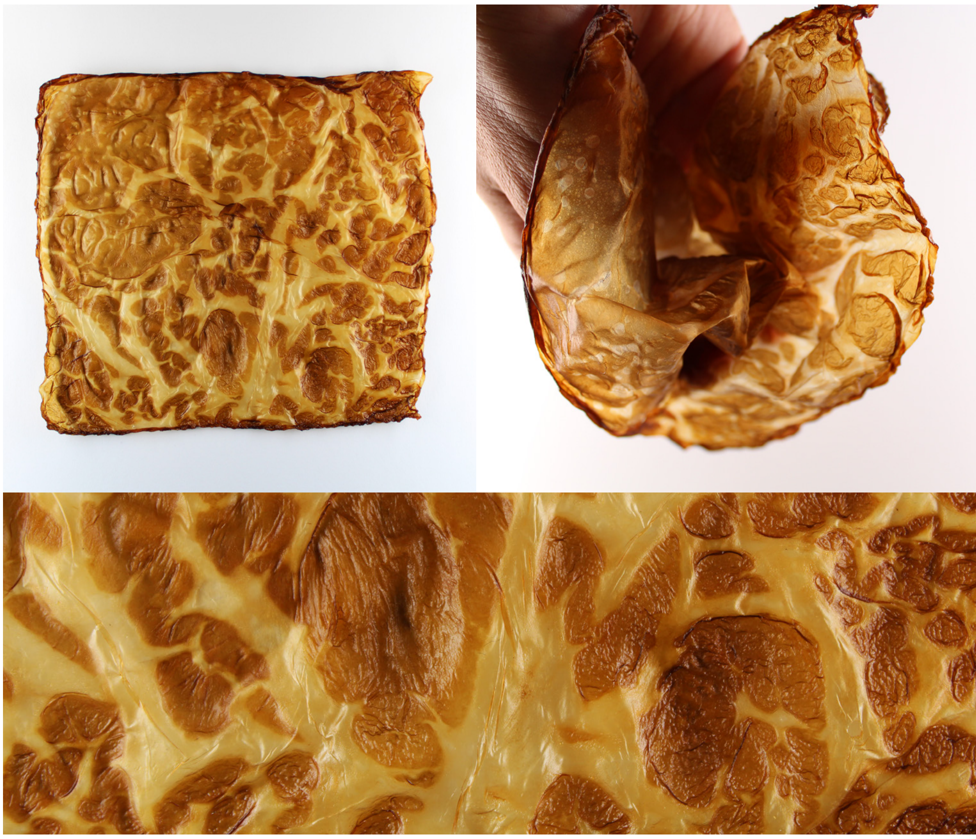


Figure 52. Flexibility 4.

Hypothesis: Glycerol and vegetable oil can generate different material properties for *S. commune* as happened with *B. robillardoides*.

Sample preparation: Four squared petri dishes were used in this experiment. Scraped mycelium from *S. commune* were grown in 200 ml of YPD. One sample contained neither glycerol nor oil (control), the second one 2% glycerol, the third one 5% oil only, and the fourth one 2% glycerol and 5% oil. After twelve days, the samples were stopped and air dried.

Result: The four samples provided compelling results as it was found that by using only glycerol or only oil, the *S. commune* would grow as separate colonies, while by adding glycerol and oil together, the colonies would expand and generate a very homogeneous material. In addition, the hydrophobicity of the material was tested and was best in the sample containing glycerol and oil.

Figure 53. Flexibility 5.

5.4.1.2 Growth

In terms of growth, most of my hypotheses derived from speculations about the type of media that could work best for the species to grow, the type of culturing method (i.e. shaken or standing liquid culture), and also the self-healing properties of the organism. My material motivations behind growing processes and behaviors had a sense of intimacy as it required me to observe and take care of the material on a daily basis. Additionally, during these experiments the working relationship with particular fungi either nourished or discontinued. There were times when I and the other experts failed to make the material grow with the media selected, or contaminations appeared, affecting the fungi's growing realm. The hypotheses also contributed to achieve a better understanding of the growing periods for each of the species and possible mechanical properties and sensorial qualities.

Hypothesis: A change in media after several days of growth can improve the thickness of *P. chrysosporium* as it grows.
Sample preparation: Two squared petri dishes were used in this experiment. $8 \cdot 10^6$ of spores from *P. chrysosporium)* were grown in 200 ml of YPD and 2% glycerol. After five days, the media was changed to one of the squared petri dishes. 200 ml of YPD and 2% glycerol was added. Three days later the samples were stopped and air dried.
Result: After changing the media once, it was found that the fungus kept growing in a layer-like manner (one on top of the other). This behavior contributed to the thickness of the material as previously presumed. It also kept the fungal species away from sporulating as was the case for the control, whose media remained unchanged.

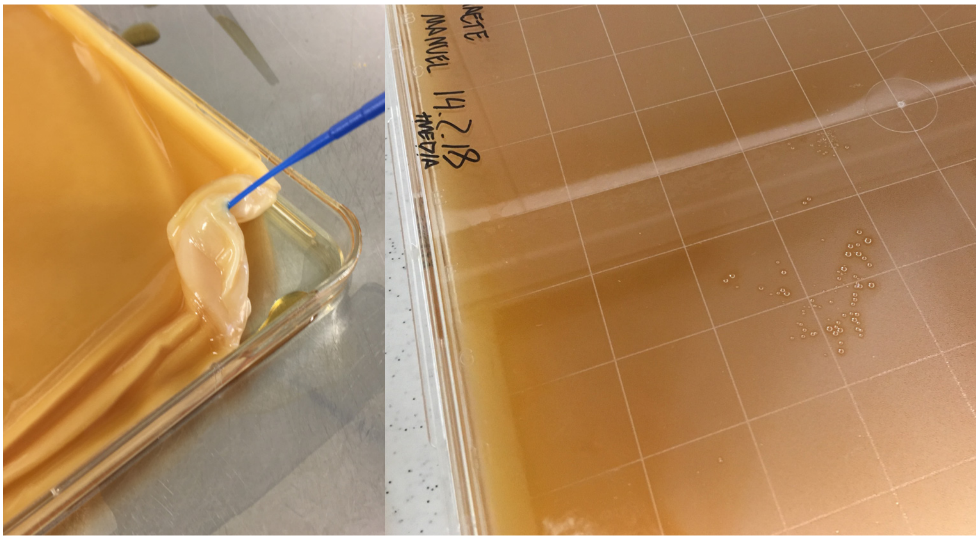


Figure 54. Growth 1.

Hypothesis: A change in media after several days of growth can improve the thickness of *B. robillardoides* as it grows.
Sample preparation: Two squared petri dishes were used in this experiment. Scraped spores from *B. robillardoides* were grown in 200 ml of YPD and 2% glycerol. After five days, the media was changed to one of the squared petri dishes. 200 ml of YPD and 2% glycerol was added.
Result: After changing the media once, it was found two days later that this action destroys the composition of the material. *B. robillardoides* grows uniformly only with the first media that it is given.

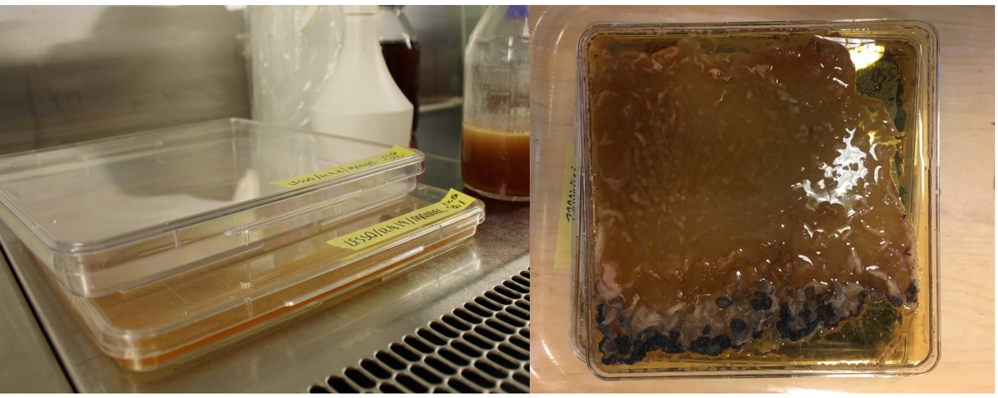


Figure 55. Growth 2.

Figure 56. Growth 3.

Hypothesis: YPD is a suitable medium for the strains *S. commune, G. lucidum, F. fomentarius,* and *P. ostreatus* to grow.

Sample preparation: Eight squared petri dishes were used in this experiment, two per strain. Mycelium was scraped from the the petri dishes containing the species and each was mixed with 200 ml of YPD. For each species, a control was done containing no glycerol and another containing 2% glycerol.

Result: *G. lucidum, F. fomentarius,* and *P. ostreatus* grew little or not at all after one week. On the other hand, *S. commune,* grew rapidly and further testing followed.

Hypothesis: In comparison to those grown as standing liquid cultures, *S. commune* can reveal different material properties to mycelium when grown as a shaken liquid culture in a flask.

Sample preparation: Two flasks containing 300 ml of YPD and scraped spores from *S. commune* were placed in the shaker to grow. After five days the flasks were removed. The mycelium grew as a pellet and was collected by filtering out the water. It was treated with a mortar to turn it into something resembling a dough, while remaining a bit moist. 50 ml of mycelium was collected and 2.5 ml of 2% glycerol was added. The collected substance was placed in a Teflon-based petri dish and placed in the 60° oven to dry for a few hours.

Result: A flexible, non-translucent, and reddish material was obtained, which was indeed different to the wrinkly and dark brown material grown in a standing liquid culture. The material felt sticky due to possibly too much glycerol.

Figure 57. Growth 4.

Hypothesis: *T. reesei* can provide different material properties to mycelium when grown in a shaken flask.

Sample preparation: Four flasks containing 300 ml of TrMM and $8 \cdot 10^6$ of spores from *T. reesei* were placed in the shaker to grow. After five days the flasks were removed. The mycelium was collected by filtering out the water, while leaving the mycelium a bit moist. 160 ml of mycelium was collected and 8 ml of 2% glycerol was added. The collected substance was placed in a big silicon-based petri dish and placed in the 60° oven to dry for a few hours.

Result: A flexible, translucent, and yellowish material was obtained, which was indeed different to the very thin and yellow material grown in a standing liquid culture. The material felt sticky due to possibly too much glycerol.

Figure 58. Growth 5.

Hypothesis: *S. commune* can self-heal if cut or ripped apart.

Sample preparation: Two petri dishes containing spores of *S. commune*, 25 ml of YPD, 2% glycerol, and 5% oil. After letting it grow for 8 days, one sample was cut, and the other sample was ripped apart. They were placed back into the petri dish to grow four days with 20 ml of YPD of new media added.

Result: After four days, it was observed that the ripped samples grew more efficiently and eventually self-healed. The cut sample grew slower and cutting may have damaged the cells more than the ripping.

Figure 59. Growth 6.

5.4.1.3 Growth in Waste

My material motivations to use waste streams and local resources as substrates originated from my wish to speculate with solid substances, especially since mycelium offers good binding properties. Some experiments were extremely challenging as they required a high level of sterilization and careful execution. Unfortunately, some of the samples produced were contaminated. Nonetheless, from a design perspective, it was fascinating to see what contaminants did as they tried to take over the growth of mycelium. The waste streams we used included textile fibers (protein-based, cellulose-based, and synthetic), willow – an agricultural waste stream - and household waste such as fruit peels and coffee grounds.

Hypothesis: Recycled fibers can act as a substrate for *T. reesei*, *P. chrysosporium* and *B. robillardoides*.

Sample preparation: *T. reesei*, *P. chrysosporium*, and *B. robillardoides* were applied to textile fibers coming from linen, silk, hemp, cotton (green and natural), and wool (grey and black) using 10 ml of TrMM and $1 \cdot 10^6$ of spores from *T. reesei* and *P. chrysosporium*. *B. robillardoides* was scraped from the petri dish. They were grown in a standard petri dish, but sixteen days later were transferred into a small petri dish to help the mycelium spread better around the fibers. This time around 150 ml of TrMM and 2% glycerol was added to each sample. Nine days later the samples were dried in the 60° oven.

Result: Cotton, silk, and wool gave the best results in terms of mycelial growth. Many samples got contaminated, even though they were autoclaved. In general, it was inferred that *P. chrysosporium* provided the best results when grown with cotton and silk.

Figure 60. Growth in waste 1.

Figure 61. Growth in waste 2.

Hypothesis: Recycled fibers can act as a substrate for *S. commune* and *P. ostreatus*.

Sample preparation: Six small petri dishes were prepared. Three small petri dishes contained scraped mycelium from *S. commune*, while the remaining three contained scraped mycelium from *P. ostreatus*. One type of textile fiber (silk, natural cotton or hemp) was added to each sample using 20 ml of YPD. Twelve days later they were dried in the 60° oven.

Result: The samples containing silk showed slow mycelial growth on both species, while those with cotton and hemp showed faster growth. Nevertheless, it was found that the previous test using *P. chrysosporium* with cotton and silk works best with the recycled fibers.

Hypothesis: *P. chrysosporium* can grow with the same material properties obtained in previous tests using a bigger format.

Sample preparation: Two big petri dishes were prepared. One containing only silk and the other one natural cotton. 75 ml of YPD were added to each sample. Six days later they were dried in the 60° oven.

Result: The sample containing cotton grew the fastest and more homogeneously than the sample containing silk. The main constraint from this type of approach was making the mycelium cover the fibers all throughout.

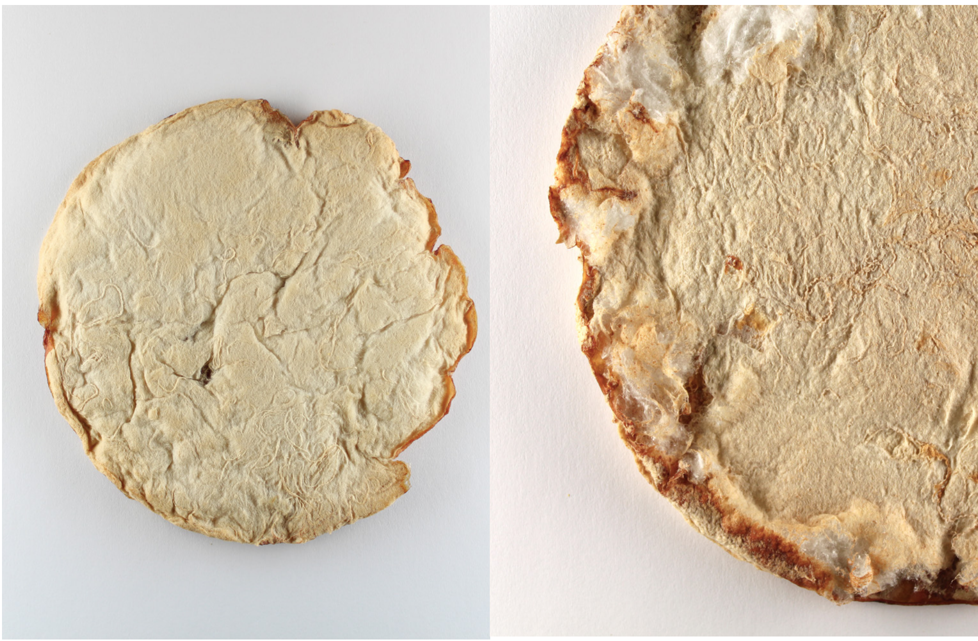


Figure 62. Growth in waste 3.

Figure 63. Growth in waste 4.

Hypothesis: Coffee grounds can act as a substrate for *B. robillardoides*, *S. commune*, G. *lucidum*, and *F. fomentarius*.

Sample preparation: For each of the four species used in this experiment, two samples were created using petri dishes (except *B. robillardoides* which had three samples). Scraped spores from *B. robillardoides* and scraped mycelium for the others were collected from petri dishes containing the fungal species. The first set of samples contained only the fungal species and coffee grounds (control). The second set of samples contained the fungal species, coffee grounds plus 20 ml of YPD, 2% glycerol, and 2.5% oil. Additionally, the third sample for *B. robillardoides* contained coffee grounds and only 2% glycerol (no oil).

Result: The samples containing *B. robillardoides* were very brittle. Growing the samples with coffee grounds might require a higher amount of glycerol than previously used. On the other hand, the samples with *S. commune* grew very well when only coffee grounds were used, but the flexibility of the material was not good. As for the samples with only *G. lucidum* and *F. fomentarius,* no growth was shown.

Hypothesis: Fruit peels can act as a substrate for *P. chrysosporium*, *B. robillardoides* and *F. fomentarius*.

Sample preparation: Six petri dishes were prepared for this experiment. Scraped spores from *B. robillardoides* and scraped mycelium from *F. fomentarius* were utilized, while $8 \cdot 10^6$ of spores were added to the samples containing *P. chrysosporium*. For each of the species, one sample with banana peel and another one with mandarin peel was created. For all of them, 20 ml of YPD and 2% glycerol were added.

Result: After eight days, the samples were taken out for drying. The experiments with banana peels was the most successful in terms of mycelial growth; however, the samples were too fragile once they dried.

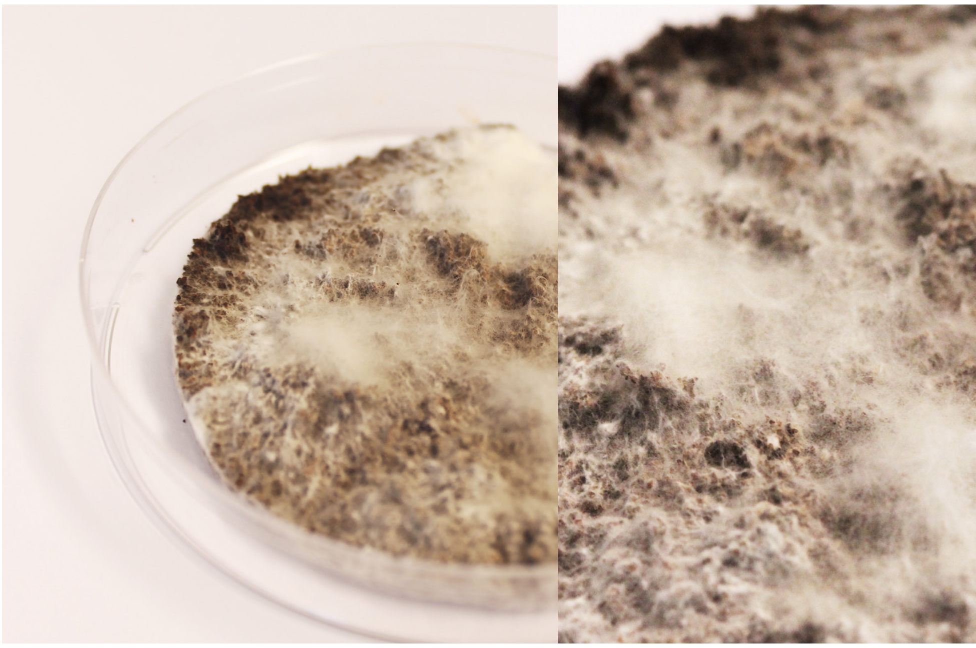


Figure 64. Growth in waste 5.

Hypothesis: Willow can act as a substrate for *B. robillardoides*, *S. commune*, *G. lucidum*, *F. fomentarius* and *P. ostreatus*.

Sample preparation: Five different species were tested in this experiment. All fungal species were grown in a petri dish using 10 ml of YPD (except *G. lucidum* which uses MEA) and 2% glycerol. Scraped spores from *B. robillardoides* and scraped mycelium for the others were collected from petri dishes containing the fungal species. For each of the five species, two samples were created, one using willow fiber bundle sheets produced with sodium bicarbonate and one using willow fiber bundle sheets made with mild alkali.

Result: The samples using *G. lucidum*, *F. fomentarius* and *P. ostreatus* grew very little or not at all. On the other hand, for B. robillardoides, the fiber bundle sheets made with mild alkali worked best – it grew very homogeneously and great strength was achieved. As for the *S. commune*, this species grew best on the fiber bundle sheet produced with sodium bicarbonate. Both, the *B. robillardoides* and *S. commune* were heat treated after growing to kill the fungi.

Figure 65. Growth in waste 6.

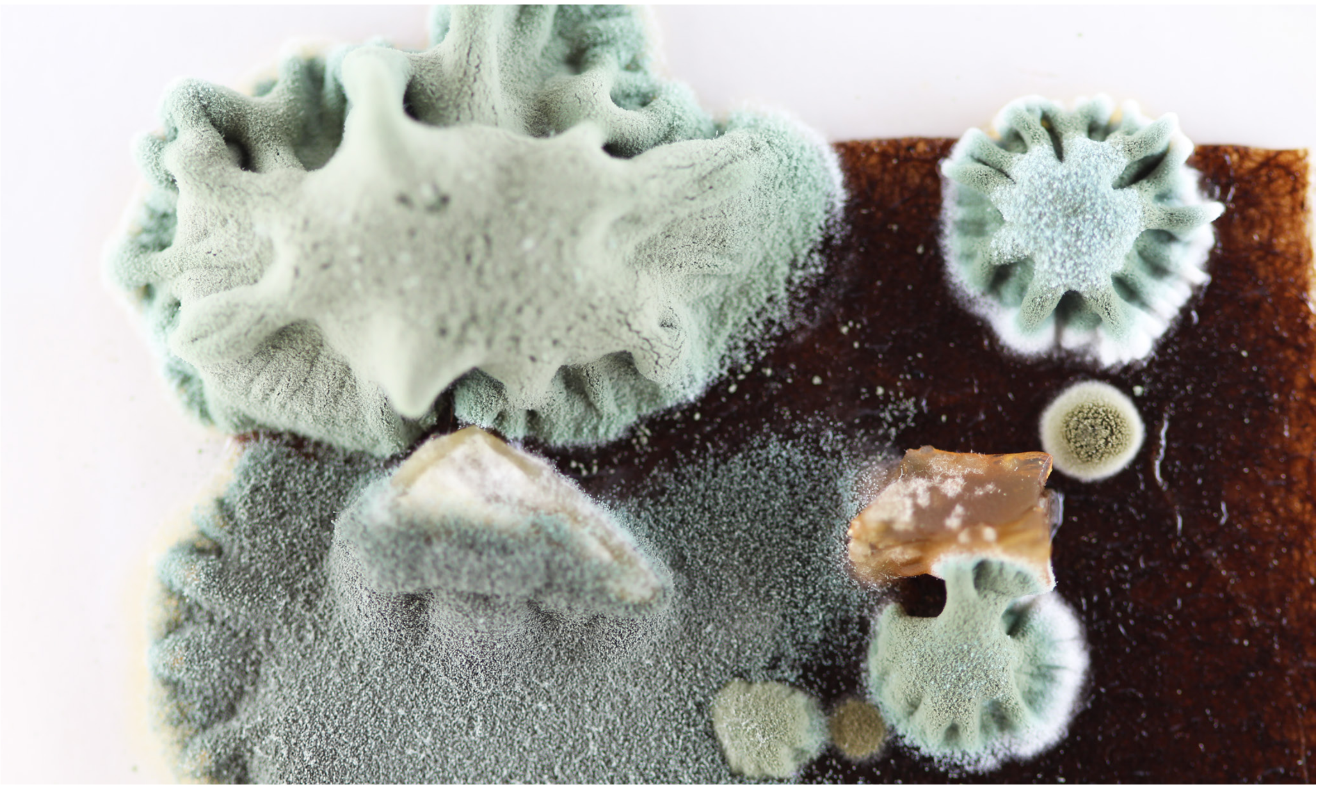


Figure 66. Contaminated sample during experimentation with willow.

Figure 67. Unknown contaminant found during experimentation with *B. robillardoides*.

5.4.1.4 Mixed Growth

The material motivations for mixed growth were driven by my desire to break the rules once again and explore what the combination of two different biological agencies would cause. For one of the experiments, I combined two different species of fungi, while for the other I introduced bacteria to enter into a biological *battle* with fungi.

Hypothesis: Mixing fungal species and layering samples can result in different material properties for *P. chrysosporium* and *S. commune*.

Sample preparation: Three squared petri dishes were prepared. One containing both $8 \cdot 10^6$ of spores from *P. chrysosporium* and scraped mycelium from *S. commune*, plus 200 ml of YPD, 2% glycerol, and 5% oil. The second one contained $8 \cdot 10^6$ of spores from *P. chrysosporium*, 200 ml of YPD and 2% glycerol. The third one contained scraped mycelium from *S. commune*, 200 ml of YPD, 2% glycerol, and 5% oil.

Result: After six days, it was noticed how *S. commune* grew as a single colony. It did not spread to other parts, neither did it mix with the *P. chrysosporium*. On the other hand, the *P. chrysosporium* and *S. commune* grown separately were placed together and taken back to grow with new media. After three days, they were air dried. The final material was slightly thicker than the one previously obtained.

Figure 68. Mixed growth 1.

Figure 69. Mixed growth 2.

Hypothesis: *G. xylinus* (bacterial cellulose) can act as an alternative organism to add strength to the fungal materials produced with *S. commune*, *B. robillardoides* and F. *fomentarius*.

Sample preparation: Seven petri dishes were prepared for this experiment. For all the samples, $6 \cdot 10^6$ of *G. xylinus* suspension was used. Scraped spores from *B. robillardoides* and scraped mycelium from *F. fomentarius* and *S. commune* were used in the other cases. Three samples contained only *G. xylinus* and were divided into 2% glycerol and oil, 2% glycerol only, and oil only. For the remaining four samples, *G. xylinus* was grown together with the fungal species. One of the samples contained *G. xylinus*, *S. commune*, 20 ml of YPD, 2% glycerol, and 5% oil. The other contained *G. xylinus*, *F. fomentarius*, 20 ml of YPD, and 2% glycerol. The last two contained *B. robillardoides* and 20 ml of YPD (one sample was given only 2% glycerol, while another one contained 2% glycerol and 5% oil).

Result: After growing for seven days, the most successful samples were *G. xylinus* and *B. robillardoides* with only 2% glycerol and the one containing 2% glycerol and oil as the strength and flexibility improved. These two samples were repeated in squared petri dishes to obtain bigger samples. *S. commune* and *F. fomentarius* grew as independent colonies on the sample. The species did not mix. From the samples containing only *G. xylinus*, the one with 2% glycerol and oil had slightly more stable material properties compared to the rest of *G. xylinus* samples.

5.4.1.5 Strength

The material motivations related to strength were one of my biggest struggles throughout the research. As I engaged in manipulating the species to build a stronger relationship, many times I felt *unheard* at the material's growing behavior when it did not respond to my expectations. However, the more experiments I conducted, the more I learned to accept fungi's agency.

This acceptance took me to think of alternate solutions. I turned to *DIY (Do It Yourself)* practices as a resource within the laboratory when biology could not do more for what I envisioned and genetic modifications were out of the question. I managed to achieve some improvements using *DIY* techniques, but to my surprise some species like *B. robillardoides* revealed unexpected experiential qualities once dried, such as becoming crinkled instead of remaining flat.

Hypothesis: Molding the material and layering can increase the material's strength for *B. robillardoides*.

Sample preparation: Six squared petri dishes were prepared using scraped spores from *B. robillardoides*, 200 ml of YPD and 2% glycerol. After growing them for seven days, one sample was used for molding it into a small bowl shape, two samples were used to layer them together, and the remaining three were mixed and molded flat to create a thicker sheet.

Result: It was found that the material became stronger by either layering or molding the material. When molded, the drying process was more challenging since the material wrinkled due to the amount of water in the sample.

Figure 70. Strength 1.

Figure 71. Strength 2.

Hypothesis: Layering can increase the material's strength for *P. chrysosporium*.

Sample preparation: Two squared petri dishes were prepared using $6 \cdot 10^6$ of spores from *P. chrysosporium* and 200 ml of YPD. One of the samples contained 2% glycerol, while the other one also contained 5% oil in addition to the glycerol. After growing them for six days, the YPD media was changed (200 ml) and glycerol and oil was added respectively (5% oil for each). Three days later, they were stopped from growing any further. The sample containing only glycerol was cut in half to layer it, while the sample containing glycerol and oil was cut into four pieces to layer it. Both samples were air dried.

Result: Layering worked well for *P. chrysosporium*. Both samples, the one with glycerol only and the one with glycerol and oil, provided different aesthetics since the one with oil was given heat. With this approach, it was found that layering the material produced the same result as changing the media since the material grows in layers when media is changed. Therefore, this test provided an alternative for future experiments as the process of changing the media could be skipped and instead grow several samples at once and then layer them manually.

Hypothesis: Layering can increase the material's strength for *S. commune*.

Sample preparation: Two squared petri dishes were prepared using scraped mycelium from *S. commune*, 200 ml of YPD and 2% glycerol and 5% oil. After growing them for ten days, they were air died. Before fully dried, they were layered and ironed to create a thicker sheet.

Result: Layering was an interesting approach for *S. commune* as the strength of the material improved and the sensorial qualities of the material such as touch and color changed compared to those samples that were only air dried. Additionally, the flexibility of the material was not compromised by the heat used for drying the material.

Figure 72. Strength 3.

5.4.1.6 Color

Our sensitivity towards the leather-like materials extended our speculation towards the use of color at later stages; once we could identify certain growing patterns with some of the species, a material motivation arose to test fungi's ability to generate pigments and its capacity to absorb dyes.

My motivations for briefly testing the topic of color derived from previous work with the strains of *F. fujikuroi* and *F. oxysporum*. Some experiments failed, yet others provided intriguing results. Color research can be considered a field of its own, and due to the limited time frame, only a few experiments on color were conducted. It is certainly an area worth exploring further.

Hypothesis: Pigments produced by *F. fujikuroi* M2040 can dye *S. commune*.

Sample preparation: Three squared petri dishes were prepared using $8{\cdot}10^6$ of spores from *F. fujikuroi* M2040 and scraped mycelium from *S. commune*. The first sample contained only *F. fujikuroi* M2040 and *S. commune* (control). The second sample contained *F. fujikuroi* M2040 and *S. commune*, plus 200 ml of YPD and 2% glycerol. The third sample contained *F. fujikuroi* M2040 and *S. commune*, 200 ml of YPD, 2% glycerol, and 5% oil.

Result: After leaving them to grow for about three weeks - due to the time it takes *F. fujikuroi* M2040 to produce the pigments - it was found that in the control, the *S. commune* grew as a single colony and color was only present in the *F. fujikuroi* M2040 (it did not mix with the rest). In the sample containing only glycerol and no oil, the *S. commune* grew again as a single colony and the color obtained from the *F. fujikuroi* M2040 was very subtle. Lastly, in the sample containing oil, the mycelium grew very little and remained in a very viscous form.

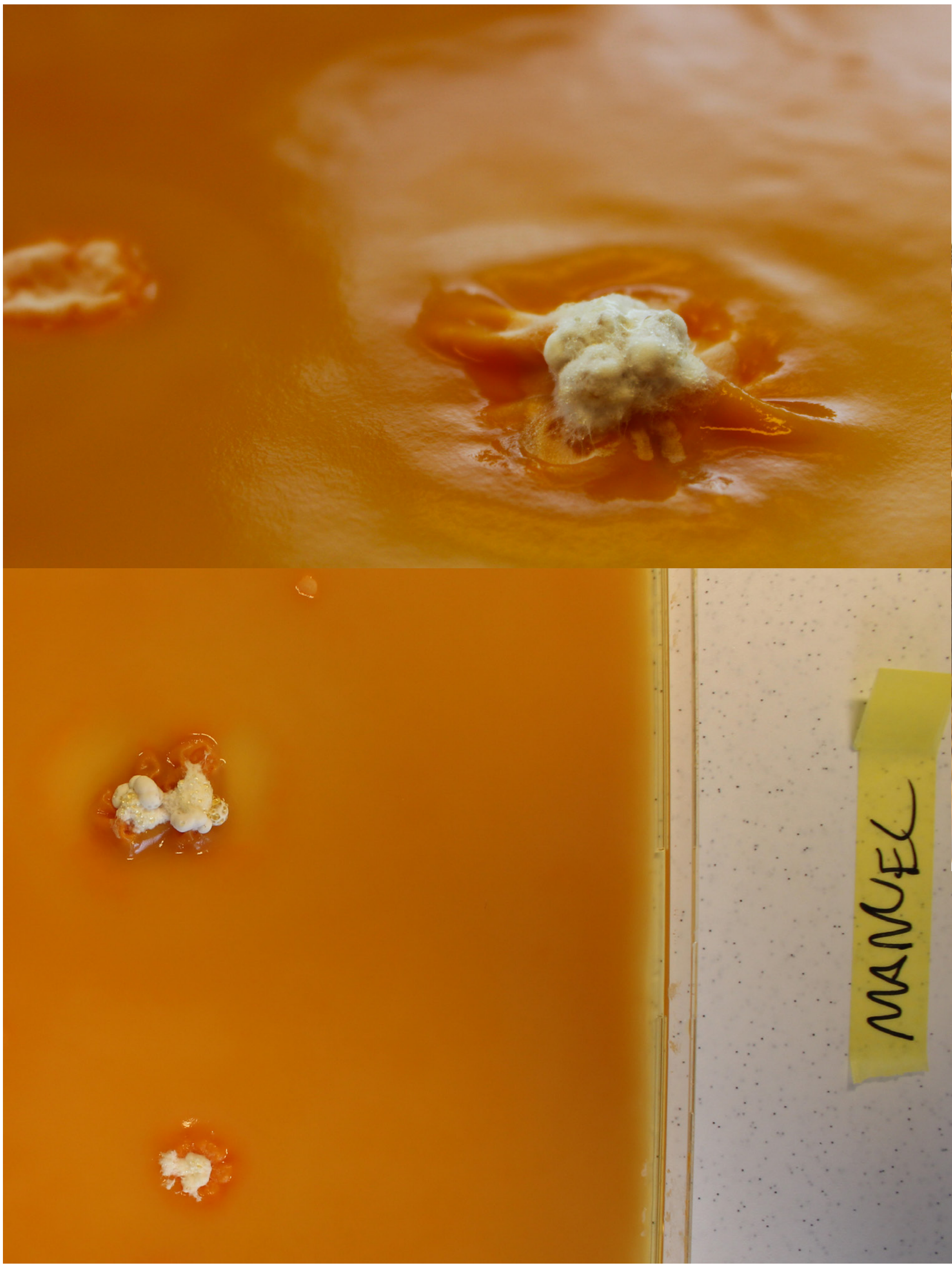


Figure 73. Color 1.

Hypothesis: Food coloring can serve as an agent to dye *B. robillardoides* homogeneously.

Sample preparation: Two squared petri dishes were prepared using scraped spores from *B. robillardoides*, 200 ml of YPD and 2% glycerol. Green and blue coloring was added to each one of them. They were left to grow for six days and then taken out for drying.

Result: The food coloring acted as a fast and easy method for dyeing the material as it saturated the sample homogeneously.

Figure 74. Color 2.

Hypothesis: Pigments produced by *F. fujikuroi* M2039, *F. fujikuroi* M2040, and *F. oxysporum* M2043 can dye *B. robillardoides*.

Sample preparation: Four squared petri dishes were prepared using $1.6 \cdot 10^7$ of spores from *F. fujikuroi* M2039, *F. fujikuroi* M2040, *F. oxysporum* M2043, and scraped spores from *B. robillardoides*. The first sample was the control which contained only *B. robillardoides* and 2% glycerol. The second sample contained spores of *F. fujikuroi* M2039 and *B. robillardoides*, 200 ml of YPD and 2% glycerol. The third sample contained spores of *F. fujikuroi* M2040 and *B. robillardoides*, 200 ml of YPD and 2% glycerol. The fourth sample contained spores of *F. oxysporum* M2043 and *B. robillardoides*, 200 ml of YPD and 2% glycerol.

Result: After growing for six days, the samples were air dried. When compared to the control, the samples containing *F. fujikuroi* M2039, *F. fujikuroi* M2040, and *F. oxysporum* M2043 provided aesthetics not obtained before with *B.* robillardoides such as different colors, textures and patterns. In all cases, *F. fujikuroi* M2039, *F. fujikuroi* M2040, and *F. oxysporum* M2043, dyed the material homogenously. When compared to the control, the sample containing *F. fujikuroi* M2040 came out to look lighter. On the other hand, the sample with *F. fujikuroi* M2039 came out orange on one side and white on the reverse, and it was the most fragile compared to the rest. Lastly, the sample containing *F. oxysporum* M2043, came out beige and had a strong resemblance to skin.

Figure 75. Color 3.

5.4.1.7 Coating

The topic of coating came to mind as part of my material motivations to achieve functional advantages such as durability and water-proof capabilities. As experts on the topic of coating were brought in for discussion, I learned that this was a material property not easy to achieve within the research time frame. In fact, in the emerging field of grown materials, natural coating agents to attain the properties I envisioned are not fully available or easily accessible. However, I opted for some *DIY* processes and used beeswax as a coating agent. While the results were not exactly what I was hoping for, it provided material qualities beneficial for some applications.

Hypothesis: Beeswax can make *P. chrysosporium*, *B. robillardoides*, and *S. commune* water-repellent.

Sample preparation: Samples of *P. chrysosporium*, *B. robillardoides*, and *S. commune* were selected to apply melted beeswax with a brush. Samples were air dried once fully covered with beeswax.

Result: The beeswax worked as a coating agent to make the material water repellent. Unfortunately, the *P. chrysosporium* sample became too fragile, while the samples for *B. robillardoides* and *S. commune* retained their integrity and offered an interesting finish which could be used for certain products (e.g. lampshade).

Figure 76. Coating 1.

5.4.1.8 Scaling Up

My material motivations were also driven by the need to get out of my comfort zone and try things a scientist would not do in a laboratory. Therefore, once our knowledge of particular species was up to a certain level, we went into growing some species on a much bigger scale, using big plastic boxes. However, our intuition played us wrong since the amplification of the living organisms at such scale did not work. In both instances, the material did not grow as we had expected. Due to the time frame, only two experiments on scaling up liquid cultures were conducted. This is an area worth exploring further.

Hypothesis: *P. chrysosporium* can grow in a bigger container.
Sample preparation: Three bottles with a total of 500 ml of YPD, 2% glycerol, and $4 \cdot 10^7$ of spores were poured in a big plastic box measuring 78 x 56 x 18 cm.
Result: After five days approximately, it was noticed how the mycelium did not grow as expected. The material grew only in some parts and not as homogenous as in the previous tests using the squared petri dishes.

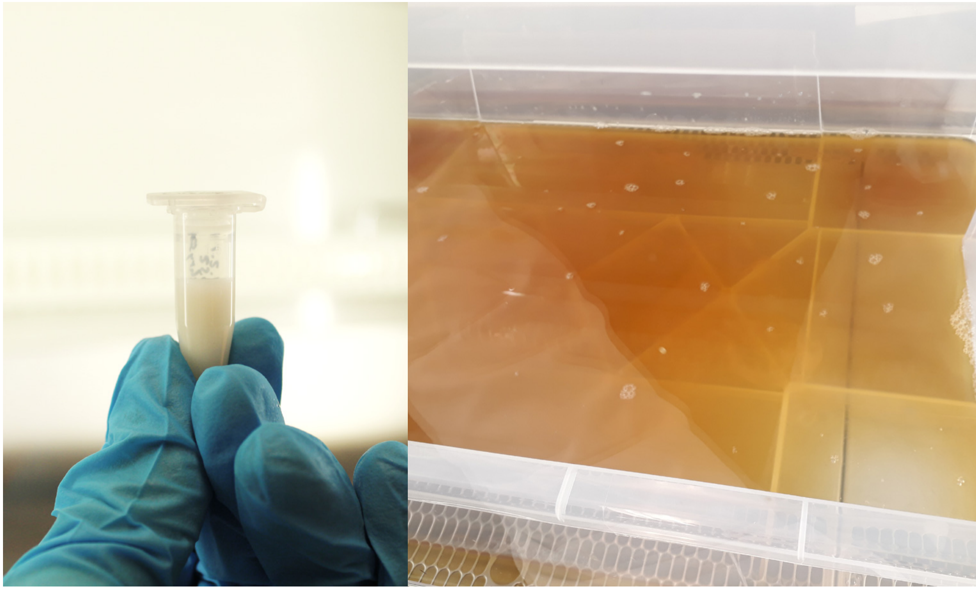


Figure 77. Scaling up 1.

Figure 78. Scaling up 2.

Hypothesis: *S. commune* can grow in a bigger container.
Sample preparation: Six bottles adding to a total of 1000 ml of YPD, 2% glycerol, 5% oil, and scraped mycelium from *S. commune* were poured in a big plastic box measuring 78 x 56 x 18 cm.
Result: Based on the previous experience with the *P. chrysosporium*, the amounts were increased. Despite this, once again the mycelium did not grow as uniformly as in the previous experiments using the squared petri dishes.

Figure 79. Bag prototype using *B. robillardoides*.

Figure 80. Material samples.

5.4.2 Evaluation of Results from the Experiments

All results from the experiments I conducted were evaluated collectively with scientists in the laboratory. Collaboration was crucial during the process of evaluation and took place, for the most part, after each experiment. Whether the experiments succeeded or failed, the biology behind it was sometimes too complex and abstract for me to comprehend alone. Integrating and sharing knowledge collectively with other experts provided a holistic learning and resulted in better framing - and reframing - of the experiments. Some of these situations included checking with a microscope the molecular composition of the species (after drying the samples) to draw conclusions or evaluate the nutrients that were given to the species.

To ease understanding of the main insights, the evaluation is presented based on the material motivations that drove each experiment: *flexibility*, *growth*, *growth in waste*, *mixed growth*, *strength*, *color*, *coating* and *scaling up*. As a general insight upon completing all experiments, we concluded in the laboratory that out of the eight species tested, *P. chrysosporium*, *B. robillardoides*, and *S. commune* were the fungal species with the most compelling opportunities in terms of material properties (mechanical) and growing behavior.

In terms of *flexibility*, we found that 2% glycerol and 5% oil were the most effective alternatives to make the material flexible when applied together or separately in comparison to those grown without any interference (control samples). For *P. chrysosporium*, using only glycerol was the best option. In this occasion, the material obtained was flexible and had a certain resemblance to plastic (e.g. acetate sheets). As for *B. robillardoides*, not only was flexibility achieved, but we observed that the sensorial qualities of the material changed drastically between samples with only glycerol and those with glycerol and oil. The different patterns provoked in myself intriguing questions such as: Who is really the designer? Are we, designers, just interventionists and nature the real (bio) designer of the future? Is this how surface design could evolve in the future? For *S. commune*, we found that the formation of colonies was affected when applying glycerol and oil. By using only glycerol, for example, colonies were more isolated and less hydrophobic. On the other hand, those samples containing glycerol and oil, brought colonies together, created a homogenous surface, and hydrophobicity was higher. From all experiments conducted, we learned that using only oil on the species did not aid in achieving the leather-like materials.

As for *growth*, the experiments conducted produced new insights for *P. chrysosporium*, *B. robillardoides*, and *S. commune* in terms of media usage, self-healing properties, and method of cultivation. In the case of *P. chrysosporium*, we concluded that by changing the media (YPD) every two to three days after growing for about five to seven days in the 28°C room, the organism grew thicker and in doing so, the species was kept from sporulating. Nevertheless, it was also found that the same effect is achieved by layering them before drying (placing one sample on top of the other). On the other hand, with *B. robillardoides*, the same principle of changing the media was applied, but we learned that doing so actually damaged the composition of the material. For *S. commune*, we determined that changing the media was not suitable since this species grows fast and this would eventually make it sporulate. This behavior was observed when paying close attention to the growing length of this species. The time to obtain a homogenous surface with *S. commune* using glycerol and oil was ten to twelve days before sporulating. For *B. robillardoides*, both with only glycerol and with glycerol and oil, the growing period was five to seven days – the same as *P. chrysosporium*, explained above. These growing periods were derived using the squared petri dish with a measurement of 22.5cm x 22.5cm in the 28°C room.

As discussed earlier, mycelium-based materials are produced either as pure mycelium from liquid cultures (standing or shaken) or mycelium-based composites. The samples mentioned in the previous paragraph were grown using pure mycelium in standing liquid cultures. I explored this cultivation method the most as it made it convenient to alter the materials' composition during the growing process. This was the case mostly with *B. robillardoides*. We found that altering the media produced various patterns (e.g. glycerol, glycerol and oil, strains of *F. fujikuroi*). Aligned with this cultivation method, is the shaken liquid culture, where the culture is aerated with a mechanical shaker. The mechanical

Figure 81. Textures from samples.

shaker was used several times to test the growing behavior of various species but was most efficient for *T. reesei*.

Due to the rapid mycelial growth of *S. commune*, self-healing properties were tested with this species. Rather than focusing on the aesthetics of the material, the aim here was to study the species' potential to self-heal. With this experiment, we concluded that cutting may damage the cells more than ripping since when ripped the material self-healed, but not so much when cut.

The cultivation method of mycelium-based composites was applied to explore *growth in waste*. The waste streams I employed came from recycled textile fibers, coffee grounds, fruit peels, and willow. Through the experiments, we observed that coffee grounds and fruit peels exhibited stable growth; however, those grown with textile fibers and willow resulted more promising in terms of material opportunities and future applications. We found that *P. chrysosporium* grown with cotton and silk provided the best results and could be studied further as an alternative to packaging material. Moreover, we learned that *B. robillardoides* and *S. commune* portrayed a steady growth when willow was used as substrate, and also the strength of the material increased. We inferred that further experimentation with willow as a substrate could provide more insights in terms of growth and techniques to increase the strength of the material.

To finalize with the topic of growth, *mixed growth* was explored to play with nature's laws. The main takeaways from these experiments came from *S. commune* and *B. robillardoides*. In the case of *S. commune*, we learned that it did not mix with other organisms during its growth. As for *B. robillardoides*, this organism displayed a homogenous growth when combined with *G. xylinus* (bacterial cellulose). The most promising sample in terms of flexibility and strength were the samples containing 2% glycerol and the one containing glycerol and oil. With this experiment, we concluded that bacterial cellulose could act as a complimentary organism to *B. robillardoides*. In addition, when the material was fully dried, the bacterial cellulose did not release the usual strong smell.

Strength was an important material motivation for conducting experiments. I explored this category by growing different samples and either layering (placing samples on top of each other) or molding the material flat by hand (mixing samples and molding). The species used in this category were *B. robillardoides*, *S. commune*, and *P. chrysosporium*. All three provided stimulating sensorial qualities and improved strength when layered. In the case of *B. robillardoides*, when molded by hand to obtain a flat surface (sometimes with the help of a rolling pin), we noticed the material would gain strength and felt similar to animal leather. If the material was molded into an even thicker surface, the end result resembled dense rubber.

In the category of *color*, *F. fujikuroi* M2039, *F. fujikuroi* M2040, and *F. oxysporum* M2043 provided some unexpected results when grown with *B. robillardoides*. Before this experiment, food coloring was used as a quick test to dye *B. robillardoides* and we noticed that the material was dyed uniformly. Inspired by this result, I decided to mix *B. robillardoides* with the strains of *F. fujikuroi* M2039, *F. fujikuroi* M2040, and *F. oxysporum* M2043). Upon completing the experiment, we found that *F. fujikuroi* M2039, *F. fujikuroi* M2040, and *F. oxysporum* M2043 dyed uniformly along with *B. robillardoides*, and new aesthetics were achieved in addition to the color. This is an area worth exploring further in the future.

Coating was covered briefly using beeswax. We found that applying beeswax to *B. robillardoides*, *P. chrysosporium*, and *S. commune* was reasonable for achieving material waterproof capabilities, but it compromised the flexibility of the material. Lastly, the species *P. chrysosporium* and *S. commune* were used for *scaling up* the material samples, but in both instances the material did not grow homogenously. We inferred that further testing and accuracy is required (e.g. running experiments with different quantities of spores and starter cultures at the large scale). Given the timeframe and scope of the thesis, these experiments were discontinued.

Upon the evaluation of results from the experiments, we concluded that the material motivations deriving from *flexibility*, *strength*, and *growth* offered the most compelling material samples and the most significant learnings given the number of experiments conducted. Within the timeframe

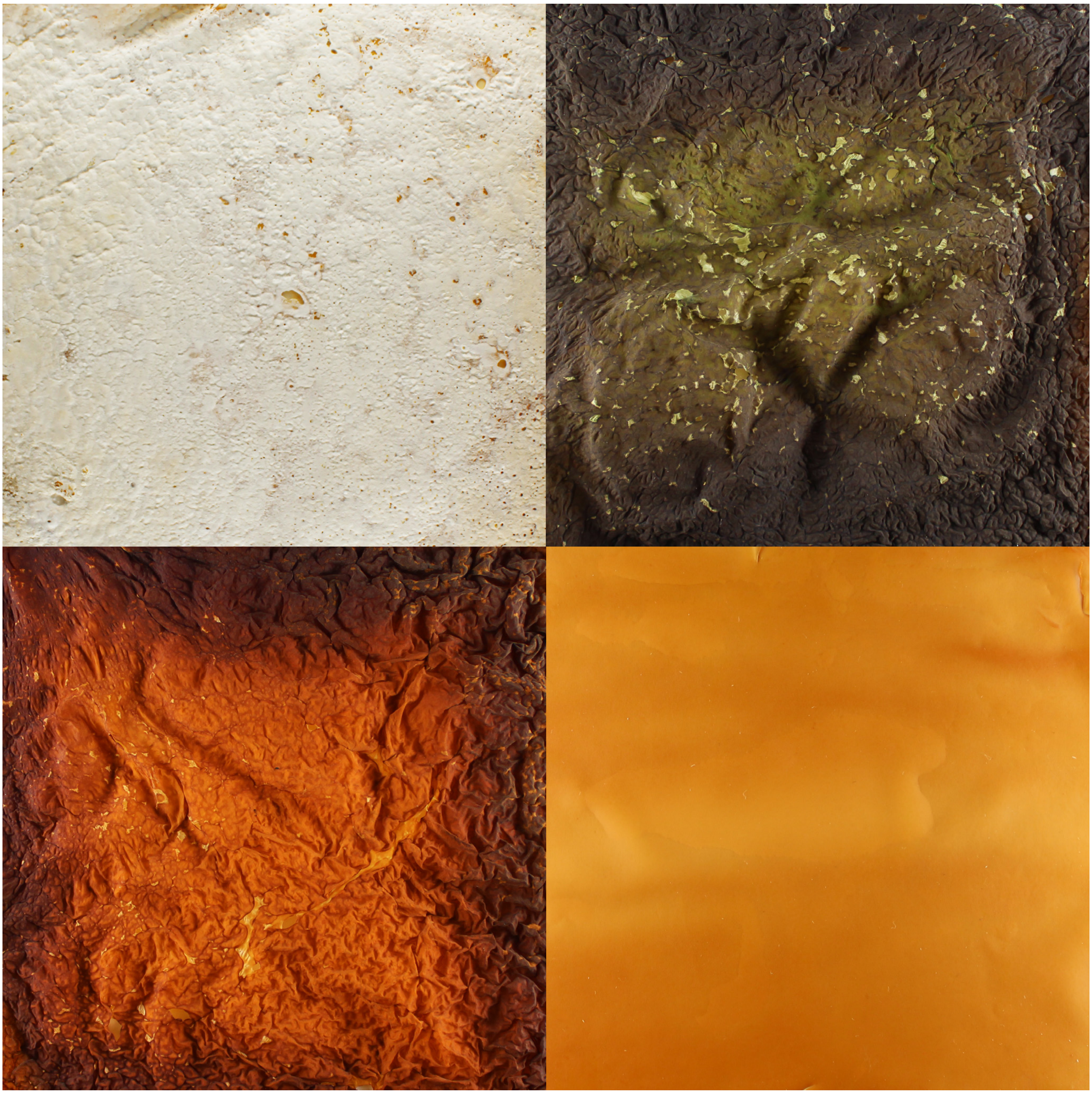


Figure 82. Textures from samples.

of the research, the samples created reached an acceptable level of flexibility. Additionally, even though *strength* still needs further research, we learned that *DIY* approaches result convenient in situations where the biological composition of the material cannot provide the desired strength. Lastly, the more we learned about the growth of different species, the more I was able to alter the experiments to obtain a diverse number of material samples.

Figure 83. Initial attempts to make the material flexible (*B. robillardoides*).

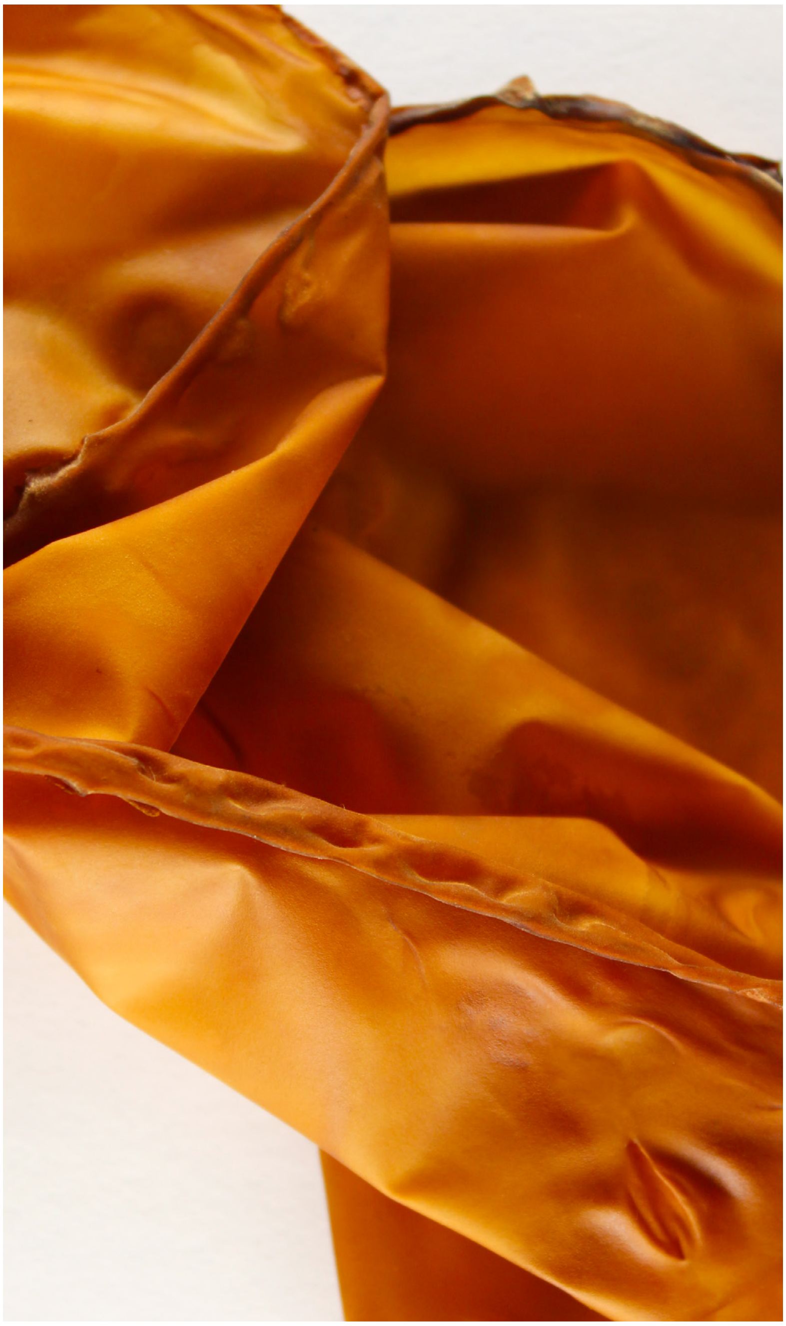
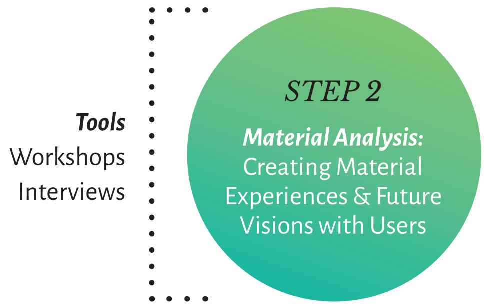


Figure 84. Material sample (*B. robillardoides*).

Figure 85. Material sample (*P. chrysosporium*).

Figure 86. Material sample (*S. commune*).



5.5 MATERIAL ANALYSIS: CREATING MATERIAL EXPERIENCES AND FUTURE VISIONS WITH USERS

The step of material analysis illustrates the introduction of design thinking to the work conducted in laboratories. As part of the material-driven process, I wanted to explore new ways to understand the work that scientists produce in laboratories. As explained earlier by Myers, in techno-scientific environments, we often focus too much on what technology can do and we leave out contextual factors (2012). For example, in the laboratory, we were constantly thinking about applications for the material, without understanding the context of the material within the everyday environment and how users would actually like to experience it.

Inspired by this opportunity, I invited users to take part in the research by conducting two workshops and ten interviews. This design approach was new for VTT Technical Research Centre. It served as an opportunity to introduce another way in which designers could advance material research and development. Just as one would reach out to users to understand better the contextual factors when designing a product or service, I was curious to know what users thought of the material samples we had created in the laboratory. I wanted to evaluate these materials with users based on their experiences and explore applications that none of us in the laboratory had thought about.

To analyze these materials, I applied the concept of *materials experience* and understood as "the experience that people have with, and through, the materials of a product" (Karana et al., 2015, p. 37). Following the theory of Karana et al. (2015), I designed the workshops and interviews to examine the material samples at four experiential levels: *sensorial*, *interpretive*, *affective* and *performative*. For a clear understanding of the terms they are defined in detail.

Materials are experienced at first hand at the *sensorial level*. It enters our human sensory system through touch, vision, smell, sound, and taste. For example, we like the soft surface of a piece of furniture, but dislike a sticky rubber phone case. Second, we can also experience materials at the *interpretive level*. This level involves

Figure 87. Step 2 of the Material Driven Design (MDD) method in the context of this research. Adapted from "Material Driven Design (MDD): A Method to Design for Material Experiences," by E. Karana, B. Barati, V. Rognoli, & A. Zeeuw van der Laan, 2015, *International Journal of Design*, 9(2), 35-54 (p. 40). Copyright 2015 by International Journal of Design. Adapted with permission.

the meanings that we give materials based on particular characteristics and traits, such as masculine, cozy, sexy, or elegant; but this does not mean that these meanings (attributes) are part of the actual properties of those materials (e.g. a material is not literally masculine or feminine). Third, materials can also be experienced at the *affective level* which focuses on our emotions – how we feel about a certain material. For example, an extremely light table might surprise us, while the imposing surface of a wall might cause us to feel scared. Emotions can greatly affect our interest in interacting with a material. Lastly, at the *performative level* is where we establish a certain relationship with material objects influenced by our sensorial perceptions, enclosed meanings, and emotions. At this level, materials are both mediated and affected by our performances with them (Giaccardi & Karana, 2015).

The emphasis of the workshops was on the sensorial level and future applications. They made possible the identification of those material samples that people found the most interesting. By the end of the two workshops, three types of material samples were identified. These three samples were then used in the interviews to learn more about the *materials experience,* this time at all four experiential levels, and find out more about possible future applications. The data obtained from the workshops and interviews are discussed next.

5.5.1 Evaluation of Results from the Workshops

Based on the evaluation of results from the experiments during the material exploration, I was able to select the material samples for the two workshops (Helsinki and Shanghai). The main objective of these workshops was for the participants to analyze the sensorial qualities of the materials and to propose future applications in a world approximately 30 years from now (2048), where one might find this material in use. This information is shown in *Figure 88*.

I distributed more samples to the participants in Helsinki since it was the first workshop after several months of experimentation and the idea was to narrow down any future experimentation after the first workshop. In Shanghai, I provided participants only four samples in total as a result from the previous workshop. Also, some improvements were made for the second workshop such as inviting the participants to tinker with the material (cutting, dipping in water, ripping, sewing, etc.), since they were all fashion students. Nevertheless, the two workshops followed the same logic and questions. Both workshops were initiated by inviting the groups to brainstorm and provide all sensorial qualities demonstrated by the fungal leather-like samples. Then, as the workshop progressed, they were asked to select one sample to analyze in more depth in order to deliver future applications for it. A set of questionnaires were given to the groups to guide their creative process and document their answers. These questionnaires included questions such as: *What are the unique sensorial qualities of the material?*, *What are the most and least pleasing sensorial qualities of the material?*, H*ow might the selected sample be implemented in the year 2048*?

Figure 88 illustrates the material samples selected by the three groups in Helsinki and the two groups in Shanghai. The samples selected came from only two species: *P. chrysosporium* and *B. robillardoides*. The species *B. robillardoides* had two versions, which were labeled as *version 1* and *version 2*.

From the evaluation of data three main insights were obtained. First, *P. chrysosporium* was the preferred sample by the participants (chosen by three groups, out of five). Second, in terms of future applications, the words *packaging*, bag, and *lamp (or lampshade)* appeared as a repeated pattern by all groups as potential applications. Third, words such as *surface*, *decoration*, *painting canvas*, and *informative material* showed how the participants perceived the material as a type of substrate for exposing information, graphics, or for playing with other elements such as light or further interaction with living organisms like fungi.

These workshops were of great significance as the partaking groups were made up of different stakeholders such as designers, engineers, and scientists with knowledge in bio-based materials, textiles, or both, and their expertise facilitated the selection of material samples to proceed with further steps in the research, discussed next.

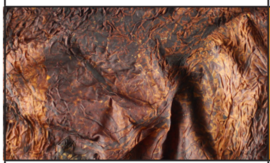
SENSORIAL QUALITIES				
Group A (Helsinki)	**Group B** (Helsinki)	**Group C** (Helsinki)	**Group A** (Shanghai)	**Group B** (Shanghai)
B. robillardoides (Version 2)	*P. chrysosporium*	*P. chrysosporium*	*B. robillardoides (Version 1)*	*P. chrysosporium*
				
Skin Wrinkly Old skin Elephant skin Transparencies Flexible Pleasant colors	Smooth Spring roll Transparent Thin Flexible Matte Plastic-like Water-resistant?	Republic Antique Plastic Smooth Bio-skin Translucent Water-resistant? Mysterious Rollable Pliable Flexible	Wrinkly Dry Patterned Fragile Rough Looks elastic Transluscent Not water-resistant	Translucent Candle-like Smooth Flexible Plastic-like Classical Food-like Caramel
FUTURE APPLICATIONS				
Grow your own furniture Second skin (products against UV light, adapts to movement) Clothes Bag Packaging Tents Hammock Informative material (e.g. controlling the pleats/ wrinkles) Adaptive, organic lightning experience (organic user interface) Multisensorial environment (for people with special needs) Immaterial products with variating material properties Prosthetic Make-up	Umbrella Plastic umbrella Tent Lamp Interior decoration (shading windows) Shoes Outdoor wear Food packaging Product cover Table cover Replacing oil-based materials Reducing waste Parachute Multiple recycling Electronics Flexible accessory (battery watch)	Protective gear Sensual underwear Lamp Water filter Packaging material (edible) Vegan pills (replacing gelatin) Plastic cover for gardenia Medical applications (wound dressing Replacing packaging (Starts to disappear when expiry date gets closer, could be used as nutrition for plants, protein source, replace plastic straw) Straw with taste	Lampshade Bag Degradable materials Medical use Art decoration Patterns on fungi surface One-off use cup holder Portable lamp Sunglasses Sunshade Theater – shadow puppet	Art installation Performance art Packaging Home decoration Book cover Painting canvas Wallpaper Jewellery

Figure 88. Results from workshops.

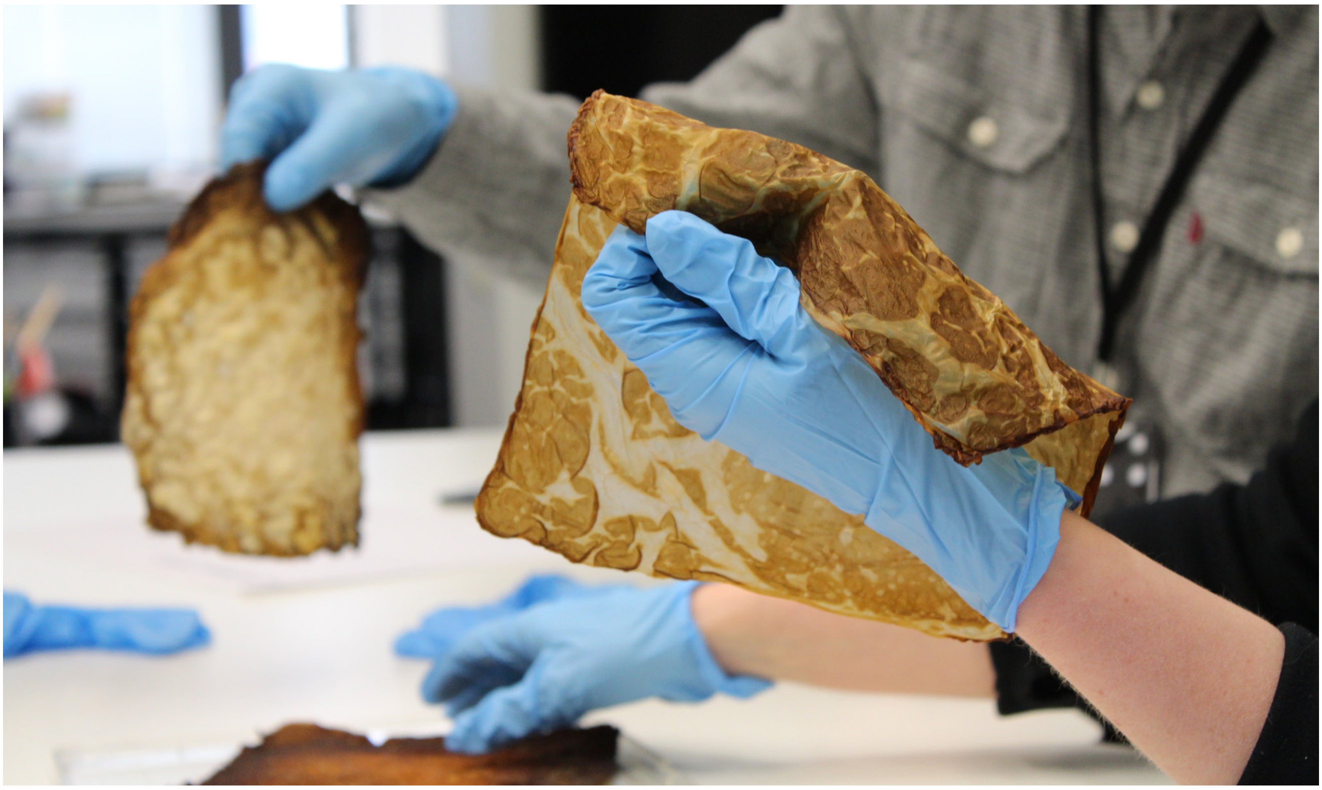


Figure 89. Participant during the workshop in Helsinki holding a sample of *B. robillardoides*.

Figure 90. Participants analyzing samples during the workshop in Helsinki.

5.5.2 Evaluation of Results from the Interviews

I conducted ten interviews with the aim to study in depth the material experiences and future applications of the samples selected by the groups in the workshops. The three samples used in these interviews came from the species *P. chrysosporium* and *B. robillardoides* (version 1 and version 2).

I provided each interviewee with one sample at a time. For each of the samples, I asked five open-ended questions related to the experiential qualities of the materials: *sensorial*, *interpretive*, *affective* and *performative* (Karana et al., 2015). These questions were: *What are the most and the least sensorial qualities of the material?*, *Is the material associated with any other material due to its similar aesthetics?*, *What kind of meanings does it evoke?*, *Does it elicit any particular emotions?*, and *How might people interact and behave with the material?* Future applications were discussed openly, taking as reference once again the year 2048, and they were organically mentioned as part of the performative level. They were asked to speculate about the material regardless of any existing constraints in present time.

The main results from these interviews are listed in *Figure 91*. The final descriptions of all insights are presented in the following section as three case studies.

Some general insights were also drawn from both the workshops and interviews. First, the smell was mentioned as the least pleasant sensorial quality of all materials, although some people felt indifferently about it, recognizing that animal leather also has a smell. In certain occasions, the smell of the fungal materials reminded people of food (e.g. pancakes, beef jerky) or something fishy. The fragility of the material was cited as neither a good nor a bad thing; participants said it all depended on the application of the material. Lastly, waterproof capabilities of the materials were mentioned by some participants, but it did not seem as relevant as the other two.

	P. chrysosporium	*B. robillardoides (Version 1)*	*B. robillardoides (Version 2)*
			
SENSORIAL	Smoothness, flexibility, translucency	Texture, pattern	3D texture, shades (layers), sturdiness
INTERPRETIVE	Warm, discreet, calm, organic, retro, elegant, old, aged, mysterious, post-disaster, experimental, classical	Strange, alive, sci-fi, unfriendly, eroded, unique, natural, surprising, decay, safari-like, creative, explorative, organic, gross	Organic, intriguing, adventurous, playful, natural, excitement, pleasant, pre-historic, peaceful, affordable, hip
AFFECTIVE	Relaxation, warmth, soothing, comfort, neutral, curiosity, calmness, summer-like, fascination, intrigued, nostalgia	Stress, intrigued, uncertainty, curiosity, repulsion, surprise, alert, discomfort, disgust, anxiety, hypnotized	Curiosity, playful, skeptical, neutral, intrigued, surprise, warm, nostalgia, uncertainty, aggression, discomfort
PERFORMATIVE	Lamp, packaging, curtains, glass (decoration), wrapping food, interiors (layers)	Lamp/lampshade, accessories, interiors, art material, decoration	Bags, clothing, accessories, jacket, dress, packaging, toy for dogs, backpack, shoes, prosthetics

Figure 91. Results from interviews.

Figure 92. Conducting one of the interviews to gather information about the material's experiences.

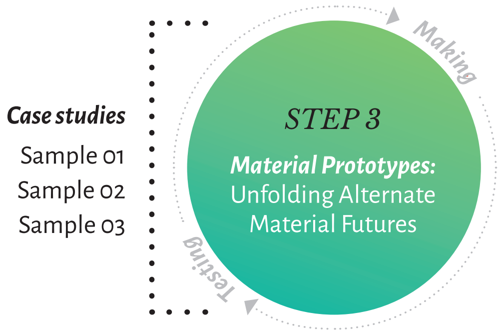


Figure 93. *Step 3* of the Material Driven Design (MDD) method in the context of this research. Adapted from "Material Driven Design (MDD): A Method to Design for Material Experiences," by E. Karana, B. Barati, V. Rognoli, & A. Zeeuw van der Laan, 2015, *International Journal of Design*, 9(2), 35-54 (p. 40). Copyright 2015 by International Journal of Design. Adapted with permission.

5.6 MATERIAL PROTOTYPES: UNFOLDING ALTERNATE MATERIAL FUTURES

This step provides a space to set forth the speculation of future applications, while also delivering the experiential qualities attached to the three chosen material samples. These materials are segmented into three case studies: *Sample 01 (P. chrysosporium)*, *Sample 02 (B. robillardoides – Version 1)*, and *Sample 03 (B. robillardoides – Version 2)*.

This material research is at its early stages; therefore, speculative design was used to show how this practice can contribute in providing questions, rather than answers for material research and development. The experiential qualities obtained for each sample allow one to contemplate the way people might experience these materials in the future.

Instead of leaving the end result to simply written data. Some images were created as a medium to mimic the application of the material without actually existing. The applications used are those that were most talked about by the participants in the workshops and interviews as well as some that were worth depicting.

The use of speculative design in such a manner provides a new way of looking at designer's work in laboratories. To a certain extent, it contributes to define the role of designers in laboratories as question creators, not solution makers. Through actual practice we, designers, are able to create a stronger bond with the work produced by scientists. I want to express the notion that with our design thinking processes we can turn ideas not into products, but into questions and open discussions for further scientific research.

Figure 94. Textures of selected samples.

Figure 95. Sample 01 (*P. chrysosporium*).

5.6.1 Sample 01 (P. chrysosporium)

5.6.1.1 Sensorial Level

Smoothness, flexibility, and translucency were identified as the most pleasant sensorial qualities of the material. Additionally, this material was constantly associated with plastic, thin paper, or rubber due to its similar aesthetics.

5.6.1.2 Interpretive Level

In this sample the color of the material played an important role when unfolding the material's meaning. The most mentioned meanings were labeled as *warm*, *calm*, *old*, *mysterious*, and *classical*.

5.6.1.3 Affective Level

Color also influenced the emotions that people associated the material with. The most stated emotions were *relaxation*, *warmth*, *fascination*, *comfort*, and *nostalgia*.

5.6.1.4 Performative Level

At the performative level, people associated most of their interaction to be through some form of packaging. In most cases, this packaging was placed into the food sector. When reflecting on the future, interesting ideas arose such as making the packaging edible, allowing fungi to shape the packaging, the packaging decomposing itself close to the expiry date of the food.

Some fewer participants related their interaction to house interiors, windows, curtains, and a canvas-like material for painting on. In these cases, it was said that the material's translucency and smoothness could be used in creative ways to enhance home environments or to paint, print, or grow on it, perhaps patterns or messages.

Other interesting applications worth mentioning were using it as a replacement for gelatin in pills (vegan pills), medical applications (e.g. wound dressing), and sensual underwear.

Figure 96. Packaging (*P. chrysosporium*).

Figure 97. Vegan pill (*P. chrysosporium*).

Figure 98. Wound dressing (*P. chrysosporium*).

Figure 99. Sample 02 (*B. robillardoides – Version 1*).

5.6.2 Sample 02 (B. robillardoides – Version 1)

5.6.2.1 Sensorial Level

The texture and the material's pattern were identified as the most pleasant sensorial qualities. The aesthetics of this material were associated with different skin types such as fish, elephant, giraffe, pig, snake, and leopard. Additionally, the pattern was said to resemble a landscape seen from above, or some sort of fried food, by several participants.

5.6.2.2 Interpretive Level

The meanings most frequently mentioned by the participants were *unique*, *sci-fi*, *strange*, *safari-like*, and *alive*.

5.6.2.3 Affective Level

The most common emotions associated with this material were *alert*, *uncertainty*, *curiosity*, *surprise*, and *anxiety*.

5.6.2.4 Performative Level

In terms of the interaction, several people said that it was a material that one would be pleased to look at but would not touch. Other people placed more emphasis on the pattern and how it had great potential to reflect light in diverse ways.

The application most talked about for this material was a lamp or lampshade. Second to this was utilizing the material for decoration or artistic purposes where light would have an important role.

Figure 100. Lampshade (*B. robillardoides—Version 1*).

Figure 101. Portable lamp (*B. robillardoides – Version 1*).

Figure 102. Curtain (*B. robillardoides—Version 1*).

Figure 103. Sample 03 (*B. robillardoides – Version 2*).

5.6.3 Sample 03 (B. robillardoides – Version 2)

5.6.3.1 Sensorial Level

The 3D texture, shades (layers), and the sturdiness of the material were named as the most pleasant sensorial qualities of the material. Several participants associated the material's aesthetics with organic and natural materials such as animal leather, tree bark, and leaves.

5.6.3.2 Interpretive Level

The most cited meanings associated to this material were *adventurous*, *pre-historic*, *playful*, *intriguing*, and *bouncy*.

5.6.3.3 Affective Level

The emotions mentioned the most were *curiosity*, *playfulness*, *skeptical*, *surprise*, and *uncertainty*.

5.6.3.4 Performative Level

People found the 3D texture to generate some kind of curiosity in them. The texture also made them reflect on nature and the possibility of the material acting as a camouflage in the woods due to its resemblance to tree bark and leaves.

This material was the one associated the most with fashion items including bags, jackets, wallets, dresses, and backpacks. Using the material for bags was mentioned the most.

Other less mentioned, but yet interesting, applications included the future use of the material as a second human skin to protect against UV light in the future, a material for prosthetics, and as informative material by manipulating the naturally occurring wrinkles of the material into visual information.

Figure 104. Bag (*B. robillardoides – Version 2*).

Figure 105. Jacket (*B. robillardoides – Version 2*).

Figure 106. Prosthetic (*B. robillardoides – Version 2*).

6: CONCLUSION

6: CONCLUSION

This last chapter covers the validity, limitations, and areas for further research of the work presented. I discuss how the findings answer my two research questions posed in *Chapter 2* against the steps utilized to accomplish the practical work to develop leather-like materials from fungi. These steps are *material exploration*, *material analysis*, and *material prototypes*. Then, I summarize the limitations of this research. Lastly, I state areas for further research.

6.1 VALIDITY OF RESEARCH

In response to the sustainability challenges found in the supply chain of current animal leather production, I decided to explore the development of leather-like materials derived fungi through the practice of biofabrication in collaboration with VTT Technical Research Centre of Finland. As a designer with sustainability and innovation at the core of my values, I perceive this topic as one which will continue to evolve as cleaner production systems become fundamental to achieve higher sustainability.

The work is located within the practice of biodesign using some of the principles of speculative design. The Constructive Design Research model by Bang et al. (2012) provided direction to the different parts of this research, while the adaptation of the MDD method guided the design process of all the experiments. The weight of the research relies entirely on the practical laboratory work conducted. It made possible the creation of leather-like materials from fungi and provided a better understanding of how designers can contribute with scientists in the future.

The two main research questions were: *what processes at the intersection of design and biology contribute to sustainable alternatives to animal leather?* and *how might this collaboration contribute to understanding the future work of designers in laboratories?* The first research question was aimed at understanding the designer's practice through biofabrication, in the context of leather-like materials derived from fungi. The second question intended to provide a pathway for the practice of design in laboratories.

The practical laboratory work in this research was divided into three parts: *Material exploration*, *material analysis*, and *material prototypes*. The first one, *material exploration*, answers the first research question. The other two, *material analysis* and *material prototypes*, answer the second question.

First, through my interaction with fungi during the material exploration, I was able to gather insights on material properties and growing behavior for the biofabrication of mycelium-based materials. This experience allowed me to mix design methods, processes, and tools with those of the scientific environment. All the months of experimentation were accomplished thanks to the learned and applied knowledge from the field of biology. It was through it that I learned to co-create and co-learn with fungi's agency. The long period devoted to the experiments made it possible to achieve a good understanding of the growing properties of the species used and possible material properties achievable within the scope of this research. As design practice extends and environmental issues become more relevant, designing with an understanding of nature's ways of production are crucial.

Second, the use of workshops and interviews during the material analysis made it possible to incorporate users and their experiences with the materials as part of the research. The benefits of making this part of the research was twofold. First, the feedback received from all the participants during these two activities allowed me to understand more about the experiential qualities attached to the materials (*sensorial*, *interpretive*, *affective*, and *performative)* and future applications. It was through these activities that the creation of a *possible future* was achieved. Second, and most importantly, these activities provided an unusual way of working for the experts I collaborated with at VTT. The workshops and interviews provided a new way to obtain data and see materials from the perspective of users and their experiences, rather than from conventional forms often attached to only functionality (e.g. technical or chemical properties). Even though conventional material thinking is useful to achieve new materialities, this one sometimes fails or becomes difficult to apply it into a product or make it useful to the end user.

Third, the conceptualization of the final samples in the context of speculative design sets a new way for designers to conduct work in laboratories. As discussed in previous sections, when working with a technology, we tend to focus on what technology can do and forget contextual factors. Introducing the topic of speculative design within VTT opened up not only a new way to work with technology, but also provided a new opportunity for design practice in this environment. Using speculation proved useful when bringing up questions and argumentations into the scientific environment as scientists develop new technologies. Speculation allows one to place the technology into several contexts, leading to a wider range of possible applications which is a need sought after by many researchers in the scientific context where the work was conducted. Through this work, it was found that speculative design results useful when triggering future applications and their implications. All these speculations were the products of practical laboratory work, workshops, and interviews, which made visible new material experiences and future applications. My main aim here was to speculate on the material uses, not products. This contributes to moving forward material-driven research within VTT.

To summarize the end result of this work, I see both my practical work from the first research question, and design's contribution to the field of science (biology) from the second question, as two areas that interlink to make the transdisciplinary collaboration possible. Below is a graph of how, upon the conclusion of this research journey, I perceive the interaction between designers and scientists in techno-scientific domains could grow in the future *(Figure 107)*.

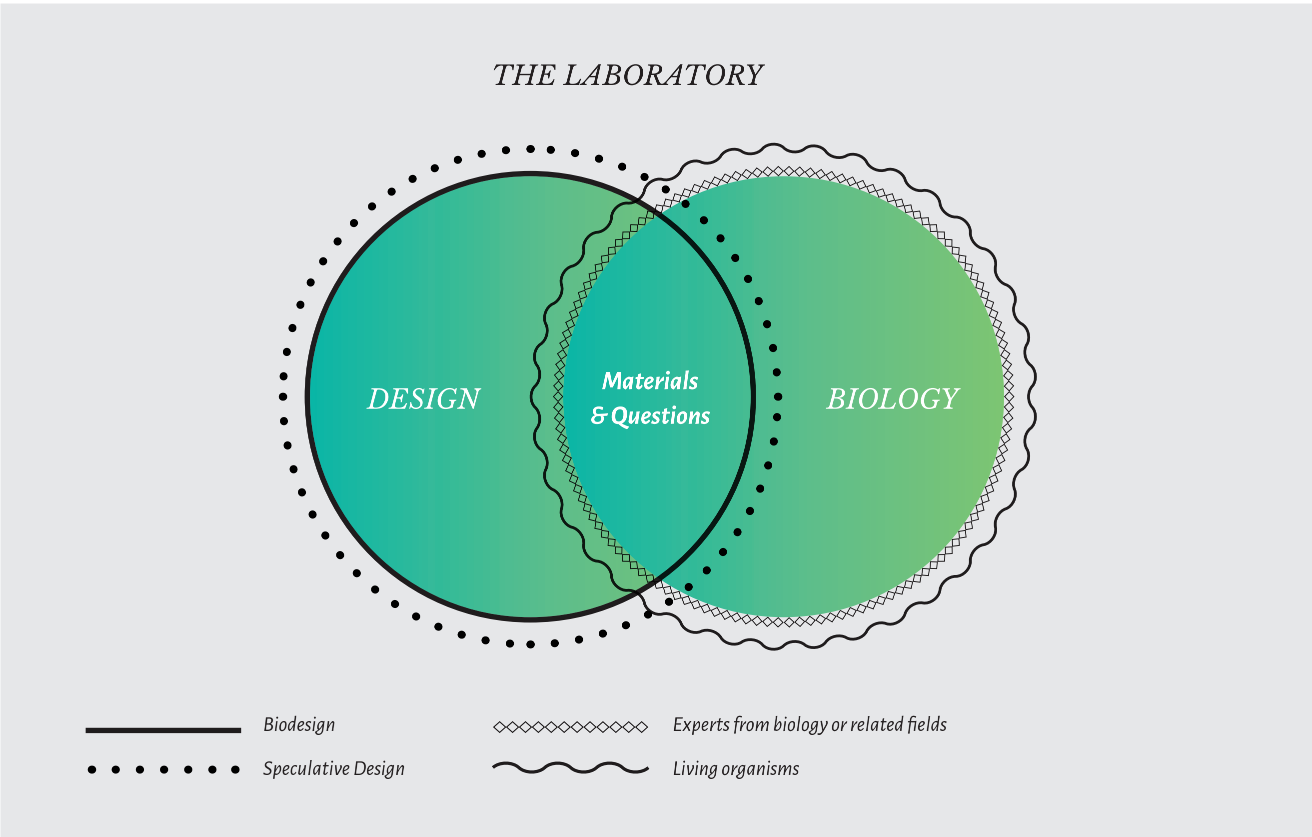


Figure 107. Personal perception of transdisciplinary collaboration at the intersection of design and biology.

6.2 LIMITATIONS OF THE RESEARCH

Over the course of this research I identified three main limitations. The first one pertains to my own design practice with the fungal leather-like materials, the second one is associated to transdisciplinary collaboration, and the third one is related to the emerging context in which the research took place.

When conducting my practical work, the process of growing materials and the months required to learn how the material behaves was very new to me and resulted in an unexpected level of complexity to the work. This included experiments taking longer than expected in order to draw conclusions and obtaining results that were not aligned with our expectations and therefore, required to be reframed and repeated. For this reason, the main focus of the experimentation was on those material motivations deriving from the material's growing behavior and the mechanical properties of strength and flexibility. All these properties were crucial for obtaining acceptable leather-like materials as prototypes for further development in the future. The areas of coating, color, and scaling up remained low priority given the time constraints.

Due to the transdisciplinary nature of the research, along the way we encountered several knowledge barriers and gaps in the collaboration which sometimes slowed down the work. This included me not having a background in biology and therefore taking longer to digest information and understand how biology works or people at the laboratory not understanding how design processes work (e.g. the value in uncertainty or going against the rules). Also involving other experts from related fields when the knowledge from the main collaborators at a certain time was not enough to answer some of the questions or needs we had (e.g. mycologists, textile engineers, or specialized technicians). Even though certain experts were brought into the work when needed, there is still plenty of unknown design and scientific language which could have maybe affected the work flow.

The practice of growing materials it is not yet defined. It is an emerging practice and so are the practices of biodesign and speculative design. Therefore, this required to be very flexible and work within a field with no set methods, processes, and techniques. Additionally, placing biology and design together proved to be a challenge throughout the entire work as their integration is still a work in progress. Nevertheless, this challenge was approached by using methods like the MDD method which offered the methodological flexibility needed and obtaining a general view on the topic of biodesign and speculative for the biofabrication of fungal leather-like materials.

6.3 FURTHER RESEARCH

I perceive this work as a small contribution towards the future development of (bio)designers. The fact that the work does not attempt to dive deep into a specific topic, but rather to offer a general view on the topic of biofabrication provides several potential areas for further research.

The first and next logical step would be to continue exploring with the selected materials themselves. With the experiential qualities obtained for *P. chrysosporium* and *B. robillardoides* thus far, existing ideas could be developed; one direction might be towards the creation of prototypes, based on the future applications obtained.

Another area for further research identified is to conduct a life cycle assessment on *P. chrysosporium* and *B. robillardoides*, and *S. commune* to gather more data regarding the sustainability components of its production.

Third, more investigative work could be elaborated with more designers in the laboratory. Their work can include conducting scientific work with other types of living organisms or applying speculative design thinking to on-going projects at VTT.

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APPENDIX

APPENDIX 1: CONSENT FORM

PHOTO & RECORDING CONSENT FORM

June 12th, 2018 / Aalto University / School of Arts, Design and Architecture

By signing in, I grant Manuel Arias Barrantes, student of Aalto University, to take photographs of my persona and make any recordings for the research purposes of Master's Thesis during the workshop "LAB-GROWN FUTURES: Designing with living materials".

I authorize Manuel as a student of Aalto University, to copyright, use and publish the same in print and/or electronically. I agree that Manuel may use such photographs and recordings with or without my name and for any lawful purpose, including for example publications related to his Master's Thesis.

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Aalto-yliopisto

PHOTO & RECORDING CONSENT FORM

June 12th, 2018 / Aalto University / School of Arts, Design and Architecture

By signing in, I grant Manuel Arias Barrantes, student of Aalto University, to take photographs of my persona and make any recordings for the research purposes of Master's Thesis during the workshop "LAB-GROWN FUTURES: Designing with living materials".

I authorize Manuel as a student of Aalto University, to copyright, use and publish the same in print and/or electronically. I agree that Manuel may use such photographs and recordings with or without my name and for any lawful purpose, including for example publications related to his Master's Thesis.

Name	Email	Signature
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PHOTO & RECORDING CONSENT FORM

October 30th, 2017 / Aalto University / School of Arts, Design and Architecture

By signing in, I grant Manuel Arias from Aalto University, the right to take photographs of me and make any recordings for the research being done for his Master´s thesis. I authorize Manuel Arias to use and publish the same in print and/or electronically with or without my name and for any lawful purpose, including for example such purposes as publications related to his Master´s thesis.

Name	Date	Signature
Alice	Tue, october 30	[illegible]
Yoki	Tue, October 30	戴雨仟
Zoe	Tue, October 30	[illegible]
Linsey	Tue. October. 30	[illegible]
Sherry	Tue, October 30	[illegible]
D. Ryanne	Tue. October. 30.	[illegible]
Ann	Tue. October. 30	黄雪冰
Hazel	Tue. October. 30	马海航.
Aurora	Tue. October. 30	邢金金
Jessie	Tue. October 30	[illegible]
Cindy	Tue. october 30	[illegible]
Diana	Tuesday 30.10.2018	[illegible]
Jia Zhuang	Tue 30.10.2018	[illegible]

A!
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PHOTO CONSENT FORM

December, 2018 / Aalto University / School of Arts, Design and Architecture

By signing in, I grant Manuel Arias from Aalto University, the right to take photographs of me during the interviews for the research being done for his Master´s thesis. I authorize Manuel Arias to use and publish the same in print and/or electronically with or without my name and for any lawful purpose, including for example such purposes as publications related to his Master´s thesis.

Name	Date	Signature
Andrea Gilly	15.12.18	
RAFFAELLA CARLUCCIO	15.12.'18	

A!
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PHOTO CONSENT FORM

April, 2019 / Aalto University / School of Arts, Design and Architecture

By signing in, I grant Manuel Arias from Aalto University, the right to take photographs of me for his Master´s thesis. I authorize Manuel Arias to use and publish the same in print and/or electronically with or without my name and for any lawful purpose, including for example such purposes as publications related to his Master´s thesis.

Name	Date	Signature
Kaarina Viita-aho	25.3.2019	[illegible]
Pezhman Mohammadi	25.3.2019	Pezhman mohammadi
Géza Szilvay	25.3.2019	[illegible]

A!
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APPENDIX 2: WORKSHOP (HELSINKI)

SOFT MATERIALS (TODAY)

Describe the materials by writing down all words that first come to mind.

LAB-GROWN
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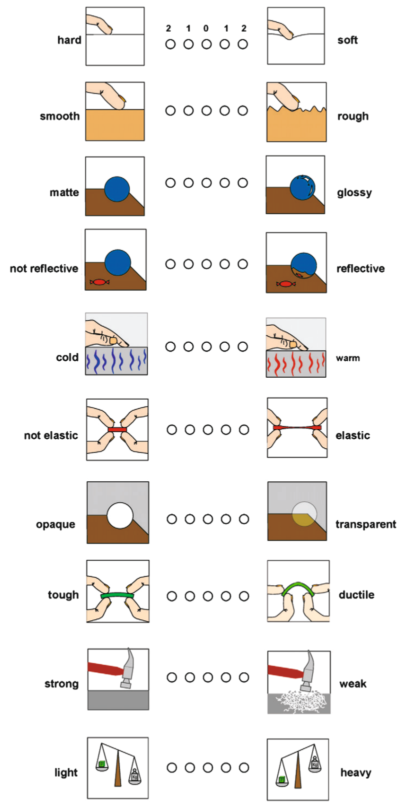
FUNGAL MATERIALS (TODAY)

Describe the materials by writing down all words that first come to mind.

LAB-GROWN
FUTURES

2. SENSORIAL SCALE

Please analyze the chosen sample using the scale below.



1. ANALYSING THE MATERIAL

Based on the previous samples analyzed, pick the one you consider having the most potential to be turned into a product or service in the year 2048 and answer the following questions.

1. What are the unique sensorial qualities of the material?

2. What are the most and the least pleasing sensorial qualities of the material?

3. Is the material associated with any other material due to its similar aesthetics?

4. Describe this material. What kind of meanings does it evoke?

5. Does it elicit any particular emotions—such as surprise, love, hate, fear, relaxation, etc.?

6. How might people interact and behave with the material?

SAMPLE 1

Place a piece of the sample you wish to analyze in a plastic bag and tape it in the square below.

LAB-GROWN
FUTURES

3. FUTURE MATERIAL VISION 2048

Use words and drawings to describe how the chosen sample “might” be implemented and turned into a product or service in the year 2048.

What would this vision require that doesn’t currently exist?

What roles or collaborators might be needed to make this vision happen?

LAB-GROWN
FUTURES

SAMPLE 2

Place a piece of the sample you wish to analyze in a plastic bag and tape it in the square below.

LAB-GROWN
FUTURES

SAMPLE 1

Describe the materials by writing down all words that first come to mind. If nothing comes up, you can use the "helping keywords" at the bottom of the page.

LAB-GROWN
FUTURES

Helping keywords: *Technical properties, sensorial properties, manufacturing processes, shape, color, function.*

SAMPLE 3

Place a piece of the sample you wish to analyze in a plastic bag and tape it in the square below.

LAB-GROWN
FUTURES

SAMPLE 2

Describe the materials by writing down all words that first come to mind. If nothing comes up, you can use the “helping keywords” at the bottom of the page.

LAB-GROWN
FUTURES

Helping keywords: *Technical properties, sensorial properties, manufacturing processes, shape, color, function.*

SAMPLE 3

Describe the materials by writing down all words that first come to mind. If nothing comes up, you can use the "helping keywords" at the bottom of the page.

LAB-GROWN
FUTURES

Helping keywords: *Technical properties, sensorial properties, manufacturing processes, shape, color, function.*

APPENDIX 3: WORKSHOP (SHANGHAI)

MATERIALS DESCRIPTION

Helping keywords: *Technical properties, sensorial properties, manufacturing processes, shape, function.*

SAMPLE 1

SAMPLE 2

SAMPLE 3

SAMPLE 4

LAB-GROWN
FUTURES

MATERIAL ANALYSIS

Based on your previous samples analysed, pick the one that you consider having the most potential to be turned into a product or service in the year 2048 and answer the following questions:

1. What are the unique sensorial qualities of the material?

2. What are the most and the least pleasing sensorial qualities of the material?

3. Is the material associated with any other material due to its similar aesthetics?

4. Describe this material. What kind of meanings does it evoke?

5. Does it elicit any particular emotions - such as surprise, love, hate, fear, relaxation, etc.

6. How might people interact and behave with the material?

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FUTURES

ENVISIONING 2048

The year is 2048, your material is now been sold, produced and manufactured. Envision through words or drawings, how this material would be used in the context of the leather and textile industry as a product or service.

IMPORTANT: *Think about who is the designer and who is the manufacturer (humans vs fungi), what type of collaborations would be needed and what this vision requires that doesn't currently exist.*

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MATERIAL TINKERING

List your main findings during the material tinkering below.

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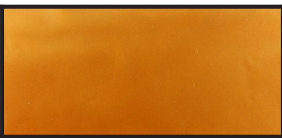
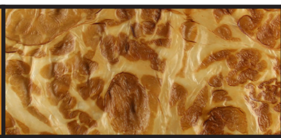
APPENDIX 4: INTERVIEWS

Interviewee: Profession:

INTERVIEW
Sensorial qualities, meanings and interaction

LAB-GROWN *FUTURES*			
What are the most and the least pleasing sensorial qualities of the material?			
Is the material associated with any other material due to its similar aesthetics?			
Describe this material. What kind of meanings does it evoke?			
Does it elicit any particular emotions - such as surprise, love, hate, fear, relaxation, etc.			
How might people interact and behave with the material?			
Any comments or suggestions?			

A!

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